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Effect of Regulated Deficit Irrigation on the Growth, Yield, and Irrigation Water Productivity of Processing Tomatoes under Drip Irrigation and Mulching

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Abstract: The application of regulated deficit irrigation (RDI) strategies with high water-saving effects for processing tomatoes is an important current research trend. In this study, we aimed to reveal the patterns of growth, yield, and irrigation water productivity (WP_I) in response to the water deficit in processing tomatoes under drip irrigation and plastic mulching in Xinjiang. To determine a more precise irrigation regime, various degrees of RDI treatments were applied to processing tomatoes in 2022 and 2023. A total of five water gradients were set up: RI (Regular Irrigation; 4500 m^3/ha), W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha). The results revealed that under RI, the yield and irrigation water productivity were 142 t/ha and 31.49 kg/m^3, respectively. Compared with RI, W_1 exhibited an increase in yield and irrigation water productivity of 12.13% and 22.39%, respectively; however, other treatments exhibited a decrease. The main reasons for the increase in yield under the W_1 treatment were: the W_1 treatment, improved photosynthetic performance, increased dry matter accumulation, and improved soil moisture conditions, thus promoting plant growth and development. In addition, in terms of water regulation at various fertility stages, moderate water deficiency at the seedling stage (S), flowering stage (F), and maturity stage (M) and rewatering at the fruit expansion stage (E) were more conducive to optimizing the yield structure. In conclusion, considering plant growth status, dry matter accumulation, yield, and WP_I, we suggested that the W_1 treatment is the optimal RDI mode most suitable for drip irrigation under mulching for processing tomatoes in Xinjiang. This study provided a theoretical and technical basis for the promotion of "water-saving and efficiency-enhancing" production of processing tomatoes.

Keywords: processing tomatoes; regulated deficit irrigation; yield; irrigation water productivity

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Citation: Xu, J.; Wan, W.; Zhu, X.; Zhao, Y.; Chai, Y.; Guan, S.; Diao, M. Effect of Regulated Deficit Irrigation on the Growth, Yield, and Irrigation Water Productivity of Processing Tomatoes under Drip Irrigation and Mulching. *Agronomy* **2023**, *13*, 2862. https://doi.org/10.3390/agronomy13122862

Academic Editor: Ivan Francisco Garcia Tejero

Received: 16 October 2023
Revised: 19 November 2023
Accepted: 19 November 2023
Published: 21 November 2023

1. Introduction

As a specialty cash crop in the arid regions of northern China, processing tomato (*Lycopersicon esculentum* Mill.) is an important raw material for the production of tomato sauce [1]. As a specialty cash crop in the arid regions of northern China, most processing tomatoes are important raw materials for the production of tomato sauces, especially in the Xinjiang Uygur Autonomous Region (XUAR), where its unique light and heat resources are conducive to increasing the content of soluble solids and the production of lycopene in processing tomatoes, which can significantly increase the nutritional quality and palatability of processing tomatoes [2]. Therefore, the processed tomatoes industry has rapidly developed in Xinjiang. At present, Xinjiang has become one of the largest production and export regions for processed tomatoes in China and the third largest in the world, with the export ratio accounting for more than 30% of the global trade, jumping up to become the most important processed tomato production base in China [3,4]. However, Xinjiang is a typical arid and semiarid region, and its annual rainfall is only one-tenth of the evapotranspiration, making water resources very scarce [5,6]. However, processing tomatoes requires a significant amount of water during their whole life cycle [7]. Over-irrigation is often applied to obtain better yields of processed tomatoes. Though it can maintain the yield, this outdated irrigation concept leads to serious waste of water resources and can significantly reduce water use efficiency (WUE) and the economic benefits of processing tomatoes [8–10].

Regulated deficit irrigation (RDI), as a proven water-saving irrigation method, may be feasible for the water-saving production of processing tomatoes in Xinjiang. RDI is a strategy for the control and utilization of water to improve WUE by reducing irrigation water during the period of crop fertility when the crop is not sensitive to water stress [11]. Studies have reported that regulated deficit irrigation (RDI) improves the water and nutrient use efficiencies of plants [12]. Alipour et al. [13] reported that RDI was effective in increasing the water productivity of kidney beans. Wang et al. [14] conducted a 2-year field experiment in 2016–2017 to study the effect of RDI on the yield and quality of radix isatidis under alpine drought conditions and reported that moderate water-deficit treatments during nutrient and fleshy root growth stages significantly increased yield and WUE. Mild water deficiency increased the content of (R, S)-thyroxine, indoxylin, and indigo; improved root quality; and enhanced the overall quality of Panax quinquefolium. Li et al. [10] investigated the effects of RDI under mulching on the growth, yield, water use efficiency, irrigation water use efficiency, and quality of pumpkin at different fertility stages under semiarid climatic conditions. The results revealed that mild water-deficit treatment at the seedling stage exhibited the highest WUE (12.47 kg/m^3) without significantly affecting yield (46 t/ha) and improved pumpkin fruit quality.

The effect of water-deficit irrigation on the production of processed tomatoes is obvious. However, previous studies are limited to greenhouses, and research on the combination of "drip irrigation" and "mulching" field cultivation in Xinjiang is limited. In 2014, Patanè et al. [15] studied water deficit tolerance in processing tomato varieties through deficit irrigation and reported that moderate water deficits had a positive effect on WUE. Valcárcel et al. [16] reported that mild water deficiency does not affect the productivity of processing tomatoes and improves WUE in Spain, and they concluded that a mildly regulated irrigation strategy is preferred to a continuous deficit irrigation strategy. A study was conducted on the effects of RDI on substrate moisture, yield, quality, and physiological traits of greenhouse-grown processing tomatoes at different fertility stages. It was reported that tomato yields were highest when moderate water deficiency was applied at the flowering and fruiting stages, whereas water deficiency during the expansion to color change stages of processing tomatoes significantly reduced tomato yield. This suggests that tomatoes are more water-tolerant during the flowering and fruiting stages [17]. Moreover, moderate RDI may maintain the size and weight of processed tomatoes and increase carotenoid levels [18]. In conclusion, it is evident that the RDI strategy exhibits significant water-saving and yield-enhancing effects in the production of processed tomatoes. However, the aforementioned studies were limited to greenhouses. Currently, drip irrigation combined with mulching has become the most important cultivation method for the production of processed tomatoes in Xinjiang [3,19,20], and the mulching planting area had reached 9.08×10^5 ha by 2016 [21]. Under-film mulching drip irrigation technology is a combination of film cultivation and drip irrigation technology. By covering the soil, the mulching film can improve soil temperature and effectively reduce evaporation between plants, while the use of drip irrigation reduces deep soil water leakage and gives the economic benefits of water saving and production. It is the advanced agricultural cultivation technology and irrigation technology, the comprehensive integration [22,23]. Therefore, as the main cultivation method for processing tomatoes in Xinjiang, it is necessary to assess the in-depth effects of RDI and mulching on the growth, yield, and irrigation water productivity of tomatoes.

Therefore, under the production method of drip irrigation combined with mulching, we conducted a 2-year field experiment in Xinjiang. We aimed to study the effects of different deficit irrigation treatments on the growth, yield, and WP_I of tomatoes to select the optimal deficit irrigation strategy. In addition, the physiological mechanisms of optimal deficit irrigation strategies to achieve water saving and high yield were further explored by revealing the coordinated characteristics of source pools, canopy light distribution, and water distribution characteristics of processing tomatoes. The results of this study will provide basic theoretical and technical support for the development of a precise irrigation system for processing tomatoes in Xinjiang and for the promotion of "quality and efficient" production of processing tomatoes.

2. Materials and Methods

2.1. Experimental Design

A 2-year (2022 and 2023) field experiment was conducted at the Experimental Farm of Shihezi University, Shihezi City, Xinjiang Uygur Autonomous Region (44°32′ N, 85°99′ E). Daily maximum and minimum temperatures and daily precipitation are shown in Figure 1. The soil in the experimental area was light loam with a 27.8% volumetric soil moisture content in the 0–40 m soil layer and a pH value of approximately 7.8. The soil contained 23.4 g/kg organic matter, 75.2 mg/kg alkaline dissolved nitrogen, 17.7 mg/kg quick-acting phosphorus, and 152.0 mg/kg quick-acting potassium. The soil conductivity was 0.15 dS/m, and the bulk density was 1.35 g/cm^3.

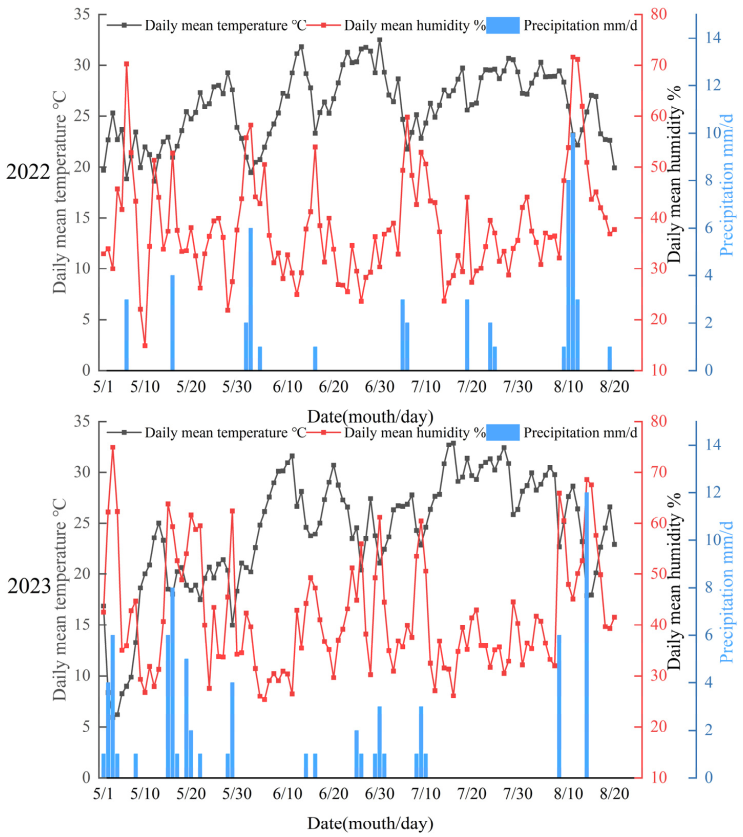

Figure 1. Meteorological data for Shihezi and Xinjiang in 2022 and 2023.

The used variety was a widely grown local processed tomato variety, "Heinz 1015" (HS1015), which was transplanted on 29 April 2022 and 1 May 2023 and harvested on 13 August 2022 and 15 August 2023, respectively. Based on the actual growth process of processed tomatoes on the field, we divided the reproductive period of processing tomatoes into four periods: seedling stage (S), flowering stage (F), fruit expansion stage

(E), and maturity stage (M). The experimental design was a one-way randomized block design with five water treatments (the amount indicates the irrigation volume of local processed tomatoes during the reproductive period): RI (Regular Irrigation; 4500 m^3/ha), W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha). The frequency of irrigation in each growth period followed previous studies. In terms of irrigation volume setting, previous studies found [24] that the irrigation range of processed tomatoes during the whole growth period fluctuated reasonably from 3938 to 4500 m^3/ha. Therefore, on this basis, we carried out small-scale water saving with the conventional irrigation amount (4500 m^3/ha) as the basis, decreasing by 7%, 14%, 21%, and 28% successively. They were W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha), respectively. Combined with the concept of regulated deficit irrigation, the optimal irrigation quantity of processed tomato in each growth stage was explored. The water regulation scheme for tomatoes at different fertility periods is shown in Table 1. Each treatment was repeated three times; therefore, the experiment included a total of 15 plots (Figure 2). The area of each plot was 15 m $\times$ 10 m. The irrigation volume was strictly controlled using a water meter. The cultivation method was traditional planting with one mulching film, two rows, and one tube (Figure 3). Narrow rows within the membrane were 0.55 m, wide rows between the membranes were 0.70 m, and the spacing between plants was 0.35 m. Drip irrigation tapes (diaphragm type) were laid in each row separately, and the distance between two drip heads of the drip irrigation tapes was 0.30 m. The design flow rate of the drip head is 2.6 L/h. The mulch used is ordinary plastic film. Two weeks before transplanting the tomato seedlings, the experimental field was mechanically deep-plowed, sprayed with herbicide, and manually cleared of debris. Fertilization strategies at all fertility stages were as per a previous study [25]. Before transplanting, phosphate and potash fertilizers were applied to the soil as basal fertilizers. The amounts of pure nutrients P_2O_5 and K_2O per hectare were 210 and 150 kg/ha, respectively. All N fertilizers were applied as follow-up fertilizers with water, and combined with the nitrogen nutrition index of previous studies, the optimized total amount of N fertilizers was 278 kg/ha. N fertilizer inputs at each fertility stage were 44 kg/ha at planting-flowering, 72 kg/ha at fruiting, 135 kg/ha at red ripening, and 27 kg/ha at seedling pulling.

Table 1. Irrigation quantity and times of each treatment in the test.

Experimental Treatment	Irrigation Amount in Fruit Seeding Stage	Irrigation Amount in Fruit Flowering Stage	Irrigation Amount in Fruit Expansion Stage	Irrigation Amount in Fruit Maturation Stage	Total Irrigation
RI	563 m^3	563 m^3	2250 m^3	1124 m^3	4500 m^3/ha
W1	484 m^3	484 m^3	2250 m^3	967 m^3	4185 m^3/ha
W2	405 m^3	405 m^3	2250 m^3	810 m^3	3870 m^3/ha
W3	327 m^3	327 m^3	2250 m^3	651 m^3	3555 m^3/ha
W4	248 m^3	248 m^3	2250 m^3	494 m^3	3240 m^3/ha

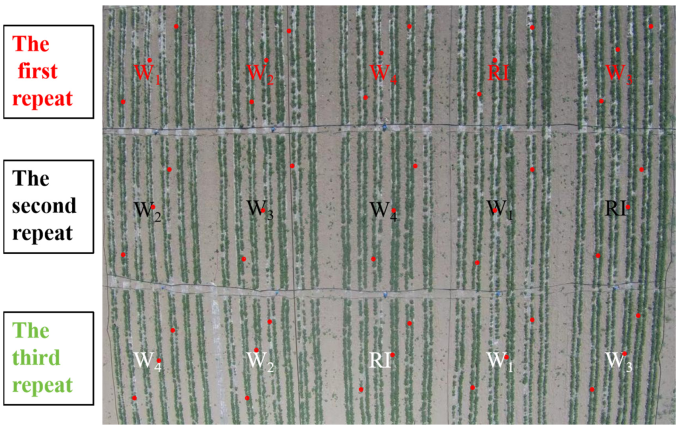

Figure 2. A map of the drip irrigation system and a picture of the canopy appearance at the seedling stage in 2023 indicate the position of the different carbon tubes.

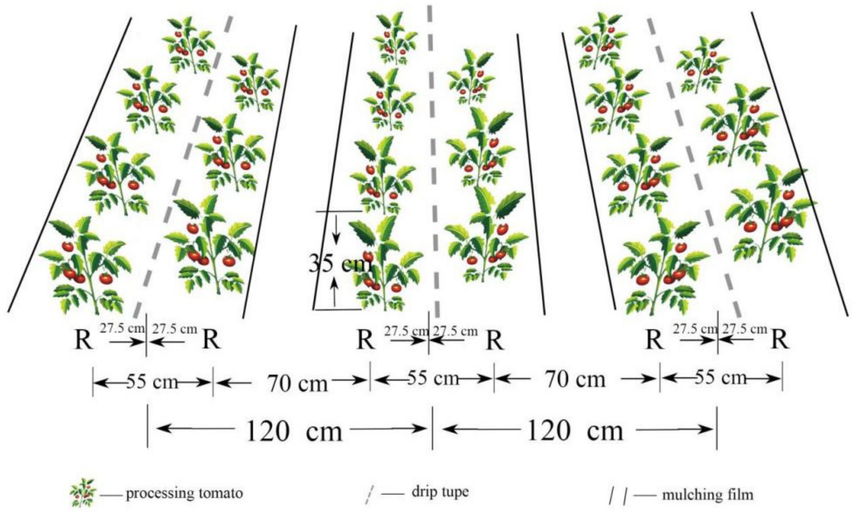

Figure 3. Planting pattern for processing tomatoes.

2.2. Sampling and Measurement

2.2.1. Yield and WP_I

Fruit yield data were recorded during fruit ripening using the area yield measurement method by selecting a 3 m × 2 m area in each treatment plot, taking three replicates, picking and weighing the fruits, and calculating the total yield. Plot yield was the weight of tomatoes we weighed on a kilogram scale after we harvested all the tomatoes from a 3-square-meter plot selected for each treatment within the experimental plots.

$$\text{Market yield (kg/ha)} = (\text{Plot yield}/3) \times 10{,}000 \quad (1)$$

The irrigation water productivity (WP_I) is the ratio between the marketable yield produced by a crop during the growing season and the irrigation water applied (IWU) in the same period [26].

$$\text{Irrigation water productivity (kg/m}^3\text{)} = \text{yield (kg/ha)}/\text{IWU (m}^3\text{/ha)} \quad (2)$$

2.2.2. Soil Moisture Status

Soil volumetric water content was measured using soil water content (SWC) measuring tubes (special tubes for Profile Probe type, Delta-T Devices, Cambridge, England) according to the method by Lv et al. [27]. It was measured at soil depths of 0–0.2, 0.2–0.4, 0.4–0.6, and 0.6–1 m. SWC was measured at four key reproductive periods of tomatoes: seedling, flowering, fruit expansion, and ripening, in 2022 and 2023. The soil moisture content was measured once before and once after each water treatment, at an interval of 7 days, and repeated three times. Each treatment was measured 21 times during the whole growth period of the tomatoes.

2.2.3. Dry Matter Accumulation and Retransportation

Three tomato plants from each treatment were selected at an interval of 7 days after the water treatment. Below the plants, soil was dug up to a depth of 0.4 m; the soil around the roots was washed, and the plants were brought to the laboratory. The tomato plants were cut into four parts: roots, stems, leaves, and fruits. These parts were placed into kraft paper bags and heated in an oven at 110 °C for 30 min, followed by heating at 65 °C until a constant weight was obtained. A one-thousandth balance is used to measure the weight [28]. Various parameters were calculated as follows [29,30].

$$\text{Dry matter distribution rate} = \text{dry matter mass per organ per plant}/\text{total dry matter mass per plant} \times 100\% \quad (3)$$

$$\text{Dry matter migration rate} = (\text{maximum dry matter mass of post-flowering organs} - \text{dry matter mass of organs at the end of fruiting})/(\text{maximum dry matter mass of post-flowering organs}) \times 100\% \quad (4)$$

$$\text{Transport rate} = (\text{maximum dry matter mass of post-flowering organs} - \text{dry matter mass of organs at the end of fruiting})/(\text{maximum dry matter mass of fruits}) \times 100\% \quad (5)$$

2.2.4. Changes in Canopy Structure and Photosynthetic Performance (Population Leaf Height, Leaf Area, Chlorophyll Content, and Photosynthetic Rate)

Population leaf height (PLH): After planting and seedling restoration, six tomato plants were randomly selected from each plot, and the height of the leaf surface was measured at 7-day intervals after each water treatment, using a tape measure to determine the height of the uppermost leaf surface from the cotyledonary node to the topmost leaf surface of the plant in its natural state [31].

Leaf area (LA) was determined using the LI-3000 Leaf Area Meter (LI-COR Inc., Lincoln, NE, USA). After planting and slowing down, three representative plants were randomly selected from each plot, and LA was measured at 7-day intervals after water treatment [32].

Chlorophyll content: The chlorophyll content of the third and fourth leaves under the growing point of the three tomato plants was measured three times at 7-day intervals after the water treatment. To extract chlorophylls a and b and carotenoids, 300 mg of fresh leaf tissue was ground in liquid nitrogen, followed by extraction with 10 mL of 96% (v/v) ethanol (Keming Biotechnology Co., Ltd., Jiangsu, China). The extracts were stored at 4 °C for 2 days in the dark, filtered, and spectrophotometrically analyzed to determine the contents of chlorophylls a and b and carotenoids by measuring absorbance at 665, 649, and 470 nm, respectively. The contents were calculated according to the method by Hartmut and Lichtenthaler [33,34].

Photosynthetic (Pn) indexes were measured at 7-day intervals after water treatment. Multiple typical days with clear weather were selected to determine the net photosynthetic rate (Pn) of the third leaf of the plant from inside to outside using a LI-6400 (LI-COR Inc., Lincoln, NE, USA) portable photosynthesizer [35].

2.3. Statistical Analysis

All data were collated in Microsoft Excel 2021 and statistically analyzed with Products and Services Solution 25 (SPSS25) using a one-way ANOVA to compare differences under different RDI treatments. Differences between the means were analyzed using the least significant difference test at the 5% probability level. All charts were generated with Origin2023 software (Systat Software, Inc., San Jose, CA, USA) [36].

3. Results

3.1. Optimal WP_I and Yield, Were Obtained under Moderate RDI

The yield (MY) of processed tomato under regular irrigation (4500 m^3/ha) (RI) level in Xinjiang was 144 and 139 t/ha in 2022 and 2023, respectively. Compared with RI, a significant increase in yield was observed when irrigation was reduced to 4185 m^3/ha (W_1), with increases of 11.35% and 12.9% in yield, respectively, in 2022 and 2023. However, when irrigation decreased to 3870 (W_2), 3555 (W_3), and 3240 (W_4) m^3/ha, the yield significantly decreased by 18.2% and 11.15%, 34.95% and 36.97%, and 34.95% and 38.96% in 2022 and 2023, respectively, compared with RI. Fruit weight per plant was significantly increased by 6.48% and 13.67% in 2022 and 2023, respectively, under W_1 compared with RI. However, it was significantly decreased under W_2, W_3, and W_4 compared with RI (Table 2). It is evident that the increase in the yield of processing tomatoes with moderately reduced irrigation may be mainly attributed to the increase in fruit weight per plant.

Table 2. Effects of regulated deficit irrigation on fruit weight per plant, yield, and irrigation water productivity of processed tomatoes (Lowercase letters indicate significant differences at the 0.05 level for HS1015 in different RDI treatments, respectively.).

	Treatment	Irrigation Amount m^3/ha	Yield per Plant kg	Plot Yield kg/3.0 m^2	Market Yield t/ha	WP_I kg/m^3
2022	RI	4500	4.67 ± 0.12 b	68.85 ± 1.0 b	144 ± 8.50 b	32.00 ± 1.89 b
	W1	4185	5.70 ± 0.3 a	73.31 ± 2.73 a	162 ± 3.79 a	38.82 ± 0.91 a
	W2	3870	4.50 ± 0.2 b	52.47 ± 1.96 c	118 ± 2.69 c	30.43 ± 0.70 b
	W3	3555	3.13 ± 0.15 c	48.46 ± 0.92 d	94 ± 2.08 d	26.35 ± 0.59 c
	W4	3240	3.00 ± 0.10 c	44.84 ± 0.89 e	94 ± 2.34 d	27.81 ± 0.72 c
2023	RI	4500	4.70 ± 0.10 b	64.32 ± 1.23 b	139 ± 5.96 b	30.99 ± 1.33 b
	W1	4185	5.57 ± 0.31 a	74.50 ± 3.29 a	160 ± 4.52 a	38.26 ± 1.08 a
	W2	3870	4.50 ± 0.2 b	56.03 ± 1.99 c	124 ± 5.34 c	32.01 ± 1.38 b
	W3	3555	2.93 ± 0.25 c	49.22 ± 1.28 d	88 ± 3.74 d	24.72 ± 1.05 c
	W4	3240	2.83 ± 0.25 c	42.81 ± 0.40 e	85 ± 3.02 d	26.27 ± 0.93 c

In terms of changes in irrigation water productivity (WP_I), the WP_I under RI was 32 and 30.99 kg/m^3 in 2022 and 2023, respectively. Compared with RI, the WP_I under W_1 was 38.82 and 38.26 kg/m^3 in 2022 and 2023, with increases of 21.31% and 23.46%, respectively. Under W_2, W_3, and W_4, WP_I exhibited a significantly decreasing trend. Overall, MY and WP_I tended to increase and then decrease with decreasing irrigation levels. This indicated that moderately lowering the regular irrigation was favorable for more satisfactory yields and quality of processing tomatoes, whereas excessively lowering the water supply reduced the yield and quality of processing tomatoes.

3.2. Accumulation, Distribution, and Transport of Biomass Play an Active Role in Optimizing Each Yield Component

Under all treatments, the accumulation of the aboveground dry matter in processing tomatoes continued to increase as the growing period progressed. Throughout the reproductive period, the rate of increase of aboveground dry matter exhibited a "fast-slow-fast" trend and began to enter the rapid growth stage in a straight line after flowering. In the seedling and flowering stages under water deficit treatments (W_1, W_2, W_3, and W_4), the quality of the aboveground dry matter of processing tomatoes was significantly lower than that under RI. The stronger the stress, the more obvious the reduction in quality. Rewatering at the fruit expansion stage narrowed the gap between treatments, particularly in W_1 (4185 m^3/ha), in terms of dry matter accumulation. The dry weight of aboveground biomass gradually returned to the level of RI and even exceeded it (Figure 4A,E).

Various water treatments allocated different proportions of dry matter to each organ before and after flowering. Overall, more dry matter was allocated to the stems and leaves before flowering, whereas more dry matter was allocated to fruits after flowering. During the 2-year field experiment, the dry matter allocation ratio of each organ before flowering exhibited a trend of leaf (40–60%) > stem (19.5%–39.21%) > fruit (<10%). Differences in the allocation ratios of dry matter in various organs and tissues of processing tomato plants among various water treatments were not significant (Figure 4B,F). The ratio of dry matter allocation after flowering exhibited the trend of fruit (49.44–55.27%) > leaf (31.53–36.47%) > stem (approximately 10%). There are significant differences in the partitioning rates of various nutrient organs and tissues of processing tomato plants among water treatments. For example, under W_1 treatment, at the ripening stage, the dry matter allocation ratio of leaves and stems was lower and that of fruits was the highest (3.6–4.61% higher) compared with RI (Figure 4C,G). Under W_2, W_3, and W_4, the dry matter allocation ratio of fruit was lower than that under RI. It is evident that rehydration after moderate water deficiency before anthesis can improve the ability of the plant to allocate more dry matter to the fruits at the later stages of fertility, thus increasing the yield.

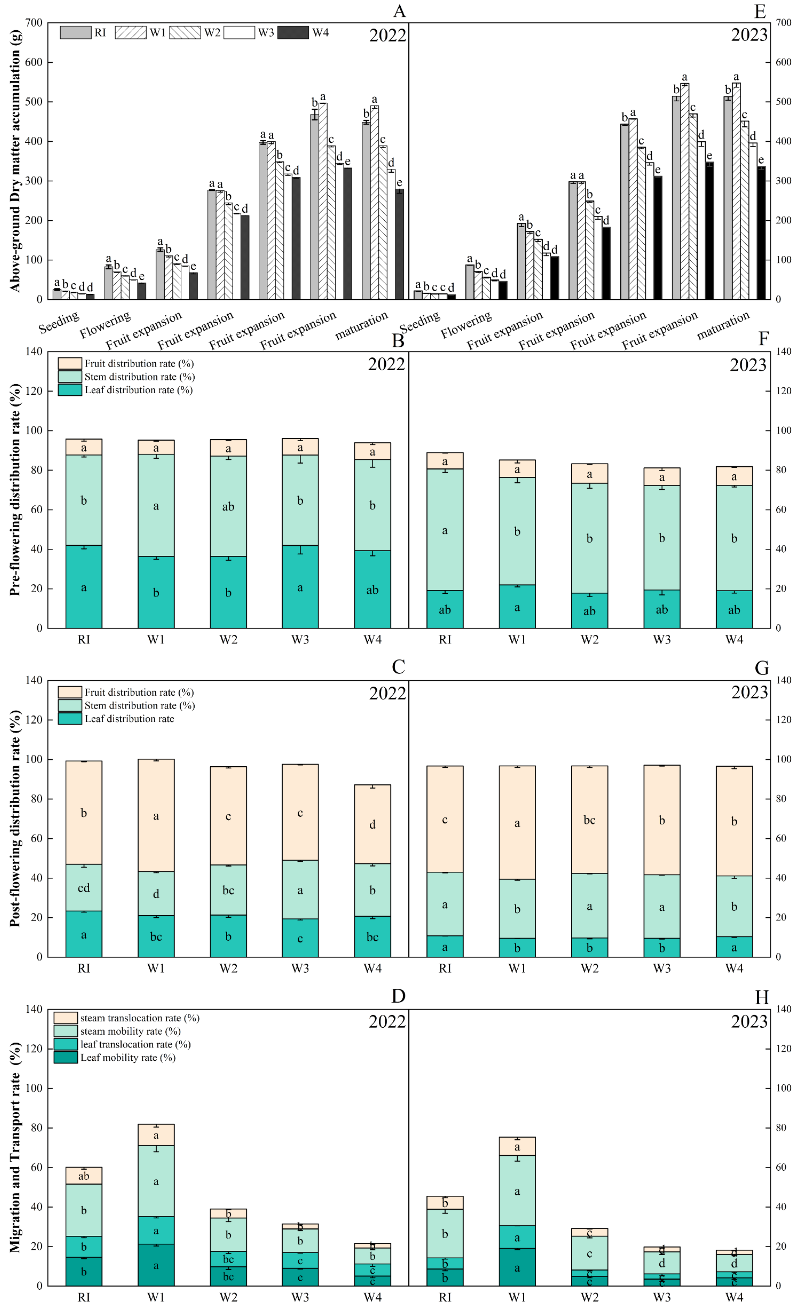

Figure 4. Effects of regulated deficit irrigation on above-ground dry matter accumulation (**A**,**E**) Pre-flowering distribution rate (**B**,**F**), post-flowering distribution rate (**C**,**G**), migration, and transport rate (**D**,**H**) of processed tomatoes. Note: Seeding, Flowering, Fruit expansion, and Maturation denote the various reproductive periods of processing tomatoes, namely, seedling, flowering, fruit expansion, and ripening, respectively. RI, W_1, W_2, W_3, and W_4 denote the different deficit-regulated irrigation treatments, namely, the local conventional irrigation amounts of RI (4500 m^3/ha), W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha). The data are the mean ± standard error of three replicates. Lowercase letters indicate significant differences at the 0.05 level for HS1015 in different RDI treatments, respectively.

The migration and transport rates of dry matter in the stems and leaves tended to increase and then decrease with the decreasing irrigation level, and the differences were significant among the water treatments. For example, these rates in stems and leaves under W_1 treatment were 38.78% and 10.02% (13.26% and 2.48% higher than that under RI) and 20.15% and 12.69% (8.52% and 4.6% higher than that under RI), respectively. Under the

W_2, W_3, and W_4 treatments, the migration and transport rates of dry matter in leaves and stems were significantly lower than those under RI (Figure 4D,H). Therefore, mild water deficiency enhanced the ability of dry matter to be efficiently transported to fruits after flowering, and moderate and severe water deficiency reduced the dry matter migration and transport capacities of stems and leaves.

3.3. Optimization of Canopy Structure and Improved Photosynthetic Performance Positively Affect Dry Matter Accumulation

PLH affects the plant's interception of light. Plants mainly produce assimilates through photosynthesis to accomplish individual development. As an important place for photosynthesis, leaves play a key role in the transformation, transportation, and transfer of assimilates. The LA determines the photosynthetically active area and amount of intercepted light energy. Chlorophyll (Chl a + b) is the basic component required for light energy absorption, transportation, and conversion in photosynthetic organs. The amount of chlorophyll content directly affects the net photosynthetic rate (Pn). The Pn of the plant reflects the growth status of the plant. Therefore, PLH, LA, Chl a + b, and Pn together reflect the photosynthetic performance of plants and affect the accumulation of dry matter.

Throughout the reproductive period, population leaf height (PLH), LA, chlorophyll (Chl a + b), and Pn of tomato populations tended to increase and then decrease. Water deficit treatments at the seedling and flowering stages resulted in decreased PLH, LA, Chl a + b, and Pn with increasing water stress. After rewatering at the fruit expansion stage, PLH, LA, Chl a + b, and Pn significantly increased under W_1 and significantly decreased under W_2, W_3, and W_4 compared with RI. It indicated that rehydration after mild water deficiency improved plant growth, optimized plant canopy structure, and improved plant photosynthetic performance. The trend of PLH, LA, Chl a + b, and Pn did not change significantly among treatments when deficit treatment was continued at the fruit ripening stage. This indicated that the water deficit at the ripening stage did not significantly affect the PLH, LA, Chl a + b, and Pn of processing tomatoes (Figure 5).

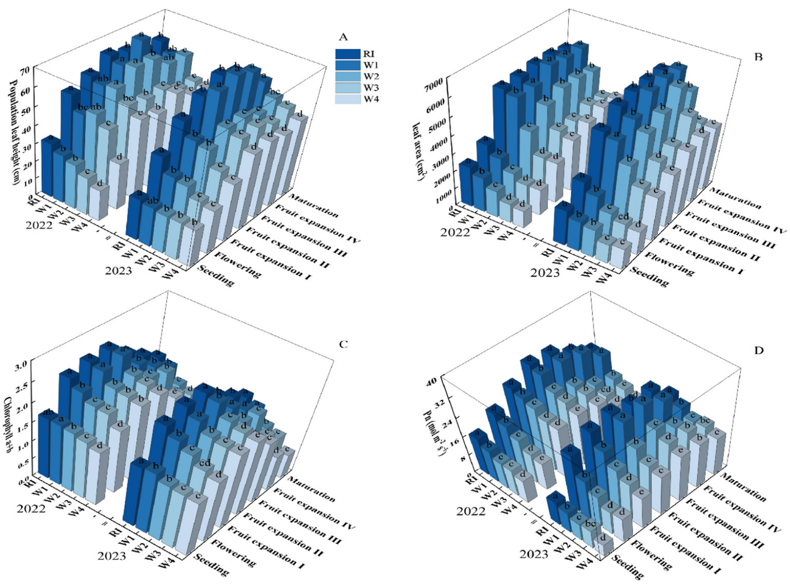

Figure 5. Effects of regulated deficit irrigation on population leaf height (**A**), leaf area (**B**), chlorophyll a + b content (**C**), and photosynthetic rate (**D**) of the processed tomato population. Note: Seeding, Flowering, Fruit expansion, and Maturation denote the various reproductive periods of processing tomatoes, namely, seedling, flowering, fruit expansion, and ripening, respectively. RI, W_1, W_2, W_3, and W_4 denote the different deficit-regulated irrigation treatments, namely, the local conventional irrigation amounts of RI (4500 m^3/ha), W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha). Data are the mean ± standard error of three replicates. Lowercase letters indicate significant differences at the 0.05 level for HS1015 in different RDI treatments, respectively.

3.4. Quantitative Analysis of SWC under an Optimal Deficit Irrigation Level Can Guide Production Practice

Loss-in-adjustment irrigation regulates plant growth by affecting SWC. The determination of the irrigation level cannot accurately guide irrigation because, in actual production, the irrigation level is easily affected by rainfall, transpiration, and other factors. Therefore, in this experiment, to guide the production practice, we quantitatively analyzed the SWC under the optimal RDI strategy. The results revealed that the W_1 treatment is the optimal RDI strategy over the whole reproductive period. The optimal SWC at the seedling, flowering, fruit expansion, and ripening stages was 35.07–38.87%, 28.03–31.73%, 29.67–32.87%, and 28.27–31.97%, respectively, in the 0–0.2 m soil layer, and 41.97–44.67%, 40.83–45.83%, 45.45–50.17%, and 42.87–44.97%, respectively, in the 0.2–0.4 m soil layer. The volumetric SWC in the 0.6–1 m soil layer did not change significantly. Future studies can refer to this SWC scale to obtain an RDI strategy for processing tomatoes under drip irrigation and mulching.

It was clear that the effective root depth and spatial and temporal distribution characteristics of SWC change along the crop stages, being 0–0.2 m in the seedling stage and increasing to 0.4 m in the maturity stage (Figure 6).

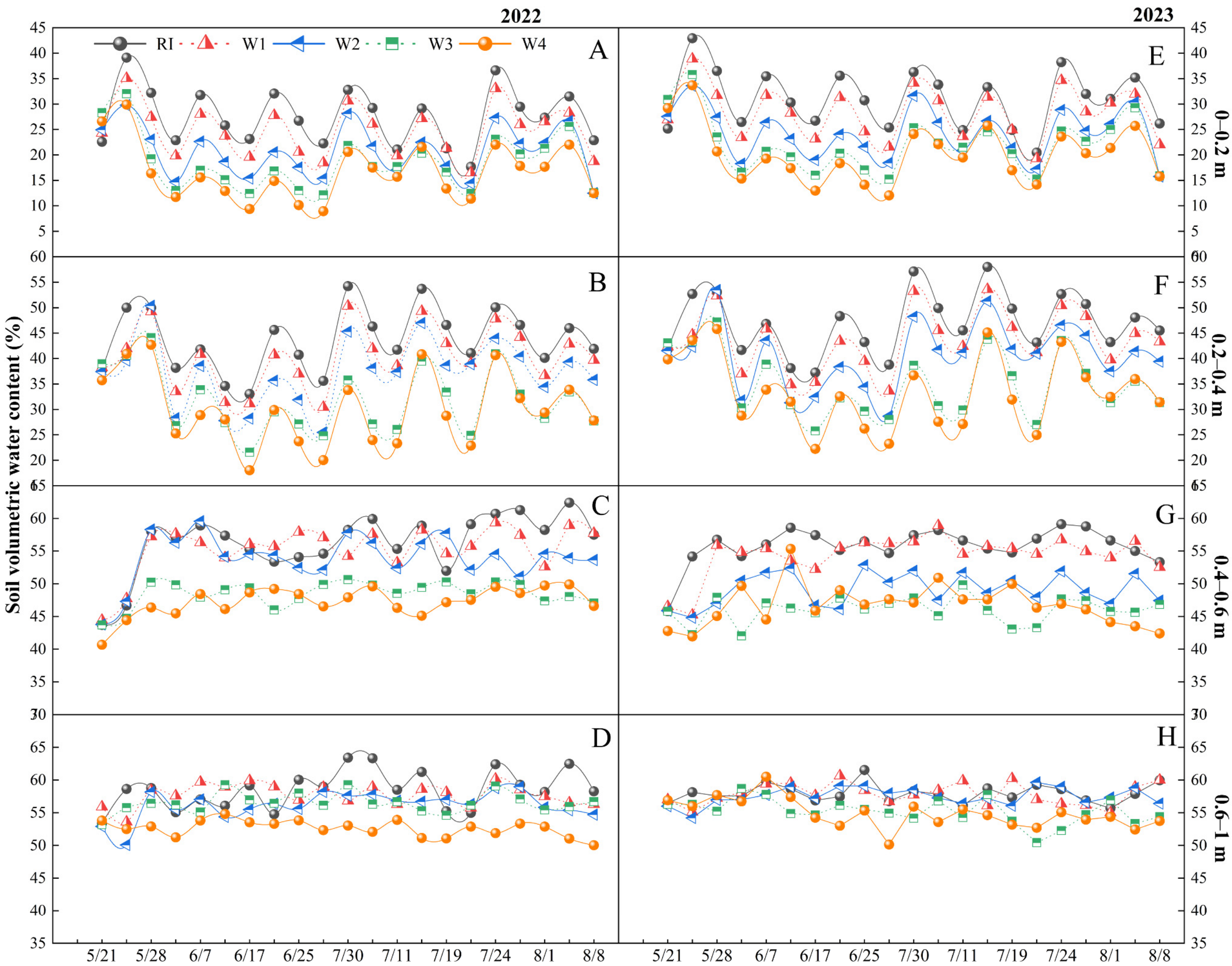

Figure 6. Quantitative analysis of 0–0.2 m (**A**,**E**), 0.2–0.4 m (**B**,**F**), 0.4–0.6 m (**C**,**G**), and 0.6–1 m (**D**,**H**) soil water content under optimal deficit irrigation. Note: RI, W_1, W_2, W_3, and W_4 denote different deficit-regulating irrigation treatments, which are the local conventional irrigation amounts of RI (4500 m^3/ha), W_1 (4185 m^3/ha), W_2 (3870 m^3/ha), W_3 (3555 m^3/ha), and W_4 (3240 m^3/ha), respectively.

4. Discussion

4.1. Optimal WUE and Yield Obtained under Moderate RDI

Studies have reported that crops are resilient to moderate water deficiency and exhibit high protective physiological behavior [8,37]. RDI enhances crop quality and water usage efficiency in production by enabling crops to endure moderate water shortages and water shortfalls at suitable non-critical fertility times with little to no yield reduction [12,38,39]. A study on RDI for processing tomatoes revealed that processing tomatoes exhibited the highest yields with mild water-deficit treatments at the S, F, and M stages, with a significant yield increase of 12.8–14.8% compared with the conventional irrigation treatments. In this study, all water treatments other than W_1 reduced the yield of processing tomatoes to various degrees. W_2, W_3, and W_4 reduced the yield by 11.15–18.2%, 34.95–36.97%, and 34.95–38.96%, respectively, compared with RI. This indicated that persistent severe water deficiency in the S, F, and M stages will significantly reduce tomato yield; after severe water deficiency, timely rehydration in the S and F stages to bring the water back to a normal level could not restore the yield to the normal level, and water deficit treatment at the M stage led to greater losses. However, rehydration after mild water deficiency increased tomato fruit yield, indicating that tomatoes have strong self-protection abilities and some tolerance under mild water deficiency treatment. This is consistent with a previous study [37]. A study on RDI for tomatoes grown in greenhouses at different fertility stages reported that moderate and heavy water deficiency during the growth stage resulted in only a 2.8–5% decrease in yield per plant, proving that water deficiency at the growth stage did not significantly reduce plant yield. Water stress at the ripening stage of fruit severely affected fruit yield, indicating that sensitivity to water stress occurs mainly at the fruit ripening stage [17]. The flowering and fruiting stages of tomatoes are more sensitive to water stress [40,41]. The occurrence of different water-sensitive periods of water deficit during fruit growth is related to fruit varieties, local cropping practices, and management practices.

Previous studies demonstrated that moderate RDI treatment was positively correlated with WUE and could significantly improve WUE [42]. Our findings were consistent with previous studies. Different levels of water deficit treatments at different fertility periods significantly affected WP_I in processing tomatoes. Moderate water deficiency increased WP_I by 21.3–23.46% compared with RI, significantly conserving water. The difference in WP_I between W_2 and RI was not significant, indicating that moderate water deficiency did not affect the crop's WP_I. WP_I decreased by 17.67–20.22% and 15.06–15.23% under W_3 and W_4, respectively, compared with RI, indicating that heavy water deficiency reduced crop WP_I (Table 2). Zhang Kun [43] showed that appropriate water stress would encourage the root system to extend downward into the soil, which would correspondingly increase the proportion of biomass allocated to the deep root system, thus inducing the root system to produce more lateral roots to absorb the unevenly distributed water in the soil, which would help to increase the vigor of the plant's root system, absorb more nutrients, and enable the plant to obtain more yields. In this experiment, the moderate water deficit significantly increased the plant yield, probably also because the moderate water deficit promoted the root system to grow downward, which promoted the plant to absorb more nutrients and water, thus increasing the yield.

4.2. Biomass Accumulation, Distribution, and Translocation Play an Active Role in Optimizing Each Yield Component

Dry matter accumulation is the basis for the formation of biological yield, and post-flowering dry matter translocation and distribution directly affect the level of economic yield. In general, the higher the economic yield of a plant, the higher the accumulation of photosynthetic products, and the more efficiently they can translocate to the harvesting organs after flowering [30]. Therefore, dry matter accumulation, translocation, and distribution have a greater impact on tomato yield. In this study, processing tomatoes were treated with light RDI at S and F stages and rewatered after flowering, and the accumulation of dry matter was significantly increased compared with RI. However, when treated with moderate and heavy water deficiency at the S and F stages and rewatered after flowering, the accumulation of dry matter increased but was significantly lower than that under RI. At the F stage, the decreases in dry matter accumulation under W_1, W_2, W_3, and W_4 were 15.73–18.89%, 27.45–35.37%, 39.56–43.58%, and 47.52–49.38%, respectively, compared with RI. With rewatering at the E stage, the dry matter accumulation increased by 6.21–6.27% under W_1 and decreased by 8.68–16.90%, 22.35–26.42%, and 28.92–32.45%, respectively, under W_2, W_3, and W_4 compared with RI. It indicated that after rewatering, a corresponding compensatory effect was observed among the treatments; the compensatory capacity of W_1 was the strongest, and water stress did reduce dry matter accumulation. This is consistent with the study by Feng [44]. This study on the effect of moisture to source-storage ratio on photosynthetic physiology as well as the yield of processed tomatoes reported that with a water deficit, dry matter accumulation in the organs of processed tomatoes tends to decrease, and the average growth rate of nutrient organ dry matter decreases.

The ability of dry matter partitioning, migration, and translocation depends on the coordinating ability of the source pools [44]. The coordination of the source-pool relationship, in turn, directly affects the level of yield [45]. The ability to harmonize the "source-pool" relationship is reflected by the rate of stem and sheath substance movement. In a study on the effect of RDI on the growth and quality of ripening lentil fruits, mild water deficiency positively affected seed dry weight [8].

In this study, the highest proportion of dry matter was allocated to leaves at the seedling stage throughout the reproductive period of the plant. It was significantly reduced after flowering, when the plant transitioned from nutritive to reproductive growth. This is consistent with a previous study [30]. Before flowering and fruiting (including anthesis), different water deficit treatments did not significantly affect dry matter allocation to fruits. However, after rewatering after anthesis, dry matter allocation to fruits under W_1 was significantly higher by 56.85–57.34% than that under RI. However, under W_2, W_3, and W_4, it was lower than under RI. In the M stage, it was clear from the treatment effects on stem partitioning rate that the RI treatment had the highest stem partitioning rate, suggesting that full-water irrigation could cause plants to develop for a longer period of time (Figure 4). In the transfer and transport of dry matter, the migration and transfer rates of dry matter in stems and leaves were significantly higher under W_1 than under RI. The higher migration rate of dry matter in stems indicated that the transfer and transport of dry matter, i.e., the "flow", in stems was smooth [26]. The transfer rate of dry matter was the highest in leaves, followed by stems, which indicated that leaves had a relatively large influence on tomato fruit yield.

In summary, when tomatoes were subjected to mild water-deficit stress and then rewatered, plant dry matter rapidly increased, and rewatering at the E stage clearly compensated for the adverse effects of the water deficit at the S and F stages. It indicated that mild RDI optimized the yield structure and facilitated the redistribution and translocation of dry matter after flowering, thus increasing the yield of tomatoes.

4.3. Optimization of Canopy Structure and Improvement of Photosynthetic Performance Have a Positive Effect on Dry Matter Accumulation

Photosynthesis is essential for plant growth, development, and reproduction. Drought stress causes many adverse effects on tomatoes, such as loss of expansion pressure, chlorophyll degradation, downregulation of the net assimilation rate, and reduction of intercellular CO_2 concentration. This results in reduced leaf expansion, root and shoot development, and biomass production, and therefore reduced fruit yield [46,47]. The leaf is the main organ for photosynthesis in crops, and LA has a great impact on crop yield. Under water stress, plant growth is inhibited, leaves do not grow normally, LA decreases, and leaf surface index decreases. Chlorophyll helps with photosynthesis. The absolute value of chlorophyll content can reflect the yield potential; the higher the chlorophyll content, the stronger the photosynthetic capacity. A significant positive correlation exists between chlorophyll content and Pn [48]. The total chlorophyll content decreased with increasing water stress. Water stress not only affects the Pn but also decreases the values of the light compensation point and the light saturation point, thus affecting the accumulation of photosynthetic assimilates [44].

In this study, the PLH and LA exhibited a trend of increasing and then decreasing throughout the reproductive period of processing tomatoes. Water deficit treatment at S and F stages significantly reduced the PLH, LA, chlorophyll content, and Pn of tomatoes, which is consistent with previous studies [32,41]. A compensatory effect was observed after rewatering during fruit expansion. Compared with regular irrigation (RI), the gradual recovery of PLH, LA, content of chlorophyll, and Pn to the normal level under W_1 even exceeded their values under RI. However, under moderate and severe water-deficit treatments, these values were significantly lower than those under RI after water restoration (Figure 5). It indicated that mild water deficiency at the S, F, and M stages and rewatering at the fruit expansion stage optimized canopy structure and improved photosynthetic performance. This resulted in the production of more photosynthetic assimilates by the plants, thus increasing dry matter accumulation and providing more potential for yield improvement.

4.4. Quantitative Analysis of SWC under Optimal RDI Levels

The water requirement of a crop at each growth stage during development can be expressed by its water consumption and can reflect the water sensitivity of the crop during each period, thus indicating the critical and peak water requirements of the crop [14].

In this study, throughout the growth and development of processing tomatoes, water consumption during each period was in the order: period E > period M > period S > period F. The water consumption of processing tomatoes during each period was in the following order: period E > period M > period S > period F. In the Xinjiang Uygur Autonomous Region, processing tomatoes were transplanted in May and entered the S-phase after irrigation with planting water. At this time, the climate is abnormal. Temperature is often low; light is weak; the plant is still in the seedling stage; and growth is slow. Plants began to sprout new leaves and exhibit fast rooting. Transpiration is low. When the soil has a mulch cover, soil moisture does not evaporate easily; soil has a strong moisture retention capacity. This stage lasts longer, for approximately 30 days (during which water consumption is less), accounting for 12.5% of the entire reproductive period. After irrigation at this stage, the optimal moisture content in 0–0.2 m and 0.2–0.4 m soil layers was 35.07–38.87% and 41.97–44.67%, respectively. In the beginning of June, processing tomatoes have their own F stage. At this stage, moderate water deficiency is more favorable for its flowering, and excessive water can cause tomatoes to continue to stay in nutrient growth, slowing down excessively toward reproductive growth and delaying the entire reproductive process. This stage lasts for a short period of time, approximately 18 days, contributing to 12.5% of the entire reproductive period. After irrigation at this stage, the optimal SWC in 0–0.2 m and 0.2–0.4 m soil layers was 28.03–31.73% and 40.83–45.83%, respectively.

In late June, processing tomatoes enter the E period, when their water demand is maximum, and it is a moisture-sensitive period. Lack of water during this period can seriously affect their yield. This is the stage where reproductive and nutrient growth coexist, with high temperatures, low precipitation, high evapotranspiration, and high water demand by plants. This stage lasts the longest in the entire reproductive period of tomatoes (approximately 40 days), and water consumption accounts for 50% of that in the entire reproductive period. After irrigation at this stage, the optimal SWC in 0–0.2 m and 0.2–0.4 m soil layers was 29.67–32.87% and 45.45–50.17%, respectively. At the end of July in the M period, mainly the accumulation of soluble solids, VC, and other substances occurs. Fruit size no longer changes; plant leaves and stalks stop growing and gradually become yellow and withered, entering the aging state. Too little irrigation during this period is not conducive to the accumulation of metabolites in the fruit, and excessive water will lead to cracking and rotting of the fruit, reducing the commercial yield of tomatoes. This stage lasts for a short period of approximately 20 days; water consumption accounts for

25% of that during the entire reproductive period. After watering at this stage, the optimal SWC of 0–0.2 m and 0.2–0.4 m soil layers was 28.27–31.97% and 42.87–44.97%, respectively (Figure 6).

In addition, different levels of RDI treatments throughout the reproductive period of tomato led to a decrease in the total water use intensity of tomato, which is consistent with the results of this study, which is consistent with the results of the previous study [49,50]. Under RDI conditions, the crop changed the distribution ratio of photosynthetically assimilated substances between the aboveground and belowground parts so that the roots absorbed more photosynthetically assimilated substances in favor of root growth and development, whereas the aboveground growth was inhibited, resulting in a reduction in leaf area, which means that the crop consumed less water even at the same transpiration rate, which in turn would lead to a reduction in water demand [51].

5. Conclusions

This experiment studied the effect of regulated deficit irrigation on the growth, yield, and irrigation water productivity of processing tomatoes under drip irrigation and mulching. It was found that W_1 showed higher irrigation water productivity and higher yield performance, which was worthy of recommendation in production. The main reasons for the increase in yield under W_1 were as follows:

(i) RDI compensated for the water deficit at the seedling and flowering stages, optimized the yield structure, and increased the single-plant fruit weight of processed tomatoes.
(ii) Moderate RDI promoted the coordinating ability of the source-sink flow and facilitated the post-flowering redistribution of dry matter and translocation.
(iii) Moderate RDI optimized the canopy structure and improved photosynthetic performance so that the plants produced more photosynthetic assimilates, thus increasing dry matter accumulation.

For production practice, we quantified the SWC levels of the optimal treatment, which were 35.07–38.87%, 28.03–31.73%, 29.67–32.87%, and 28.27–31.97% in the 0–0.2 m soil layer and 41.97–44.67%, 40.83–45.83%, 45.45–50.17%, and 42.87–44.97% in the 0.2–0.4 m soil layer for the seedling, flowering, fruit expansion, and ripening stages, respectively.

Author Contributions: The contributions of each author are as follows: Conceptualization, J.X., and M.D.; methodology, S.G., and X.Z.; software, W.W., and Y.Z.; validation, W.W., and Y.Z.; formal analysis, Y.C., and S.G.; writing—original draft preparation, J.X., and X.Z.; writing—review and editing, J.X., and Y.C.; visualization, W.W.; supervision, M.D.; project administration, M.D.; funding acquisition, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of Xinjiang Joint fund project (U190315).

Data Availability Statement: Data are available from the authors upon request.

Acknowledgments: The authors would like to thank all the reviewers who participated in the review. We would also like to thank Shengqun Pang, Changhong Li, Yuanling Yang, Yundan Cong, Yonghui Yang, and Xiaowen Zhao for their help in my experiment.

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

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