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Evaluating Effects of Regulated Deficit Irrigation under Mulched on Yield and Quality of Pumpkin in a Cold and Arid Climate

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Abstract: As the most effective irrigation method in arid and semi-arid regions, drip irrigation under mulch could general comprehension of the production efficiency of agricultural irrigation water, and reduce agriculture consumption of water resources. The paper has carried out an investigation over a two year period (2020–2021) in a semi-arid climate in the Hexi Oasis region of China, aiming at determining the influence of regulated deficit irrigation (RDI) under mulch on the growth, yield, water use efficiency (WUE), irrigation water use efficiency (IWUE) and quality of pumpkin at different growth stages. A total of nine treatments with three irrigation levels (75–85% field capacity, 65–75% field capacity, and 55–65% field capacity) have been used in four growing periods of pumpkin (seedling, vine extension, fruit expansion, and maturation stages). The results have shown that light water deficit treatment at the seedling stage had the highest water use efficiency (12.47 kg/m^3) without significantly affecting yield (45,966.90 kg/ha), and improved pumpkin fruit quality. It was concluded that light water deficit at the seedling stage and adequate irrigation at other development stages was the optimal irrigation strategy for pumpkin growth. The results of this research provide theoretical and technical support for efficient water-saving plantation and industrialization of pumpkin in the Hexi Oasis.

Keywords: yield; quality; water use efficiency; irrigation water use efficiency; water deficit; pumpkin

1. Introduction

Pumpkin (*Cucurbita pepo* L.), a member of the Curcurbitaceae family, is a trailing annual herb, which originated in the Americas and is now widely grown throughout the world [1]. Pumpkin is considered one of the most significant economic vegetable crops in the world, not only for its high food value [2] but also for its great medicinal value [3] due to its rich content in various chemical substances [4]. According to the United Nations' Food and Agriculture Organization (FAO) in 2020, the global production quantity of pumpkin was 27.96 million tons, of which China accounts for about 7.48 million tons (about one-fourth of the global production), and together with India accounted for over 45% of the pumpkin global production [5].

Water resources are one of the most fundamental elements of agricultural production [6]. In recent decades, the world's fast population increase, urbanization, and industrialization had exacerbated the conflict between availability and demand for water resources. [7]. With over 40% of water resources used for agricultural irrigation each year [8], the rational and optimal use of irrigation water, the improvement of agricultural water use efficiency, and the development of sustainable agricultural systems are urgent issues in arid, semi-arid, and water-scarce regions [9,10].

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Currently, regulated deficit irrigation (RDI) has become one of the most reliable water-saving irrigation management strategies in arid and semi-arid environments. RDI is a water control strategy that refers to the application of a certain level of water stress to the crop at a specific growth stage, in order to enhance water use efficiency (WUE) to reduce irrigation water use [11]. Numerous researches have been conducted on maize [12], potato [13], soybean [14] tomato [15,16], and pepper [17] as well as other crops [18], while it was found that RDI might reduce crop yield [19], the proper amount of water regulating deficit applied at the correct time can effectively increase water productivity [20,21] and improve fruit quality [22]. In the meantime, drip irrigation under mulch combines the advantages of drip irrigation and conventional plastic film mulching technology and is widely used in arid and semi-arid locations of western China [23,24]. Drip irrigation is the most reliable and efficient irrigation method because it is consistent, steady, water-saving, fertilizer-saving, reduces deep percolation [25,26], and improves the salinity of the land [27]. Mulching can significantly decrease ineffective evaporation of soil water [28] increase the efficiency and quality of drip irrigation, control soil salt accumulation [29], regulate soil temperature for crop growth and development [30], reduce weed growth in the field, and increase crop yield [31]. It is important to note that plastic film mulching technology can lead to plastic waste contamination and needs to be properly recycled and disposed of at the end of the growing season to avoid threatening the environment and public health.

Although many scholars have conducted numerous studies on the effects of yield and water use efficiency of different crops under RDI, there are fewer studies on pumpkin, especially under drip irrigation under mulch. And because of the crop-specific effects of RDI, determining the best irrigation strategy for a crop in the area requires years of field trials [32,33]. Therefore, the objectives of the study were to determine (1) the effect of RDI under plastic film mulch on pumpkin growth, yield, WUE, and quality and (2) the optimum irrigation strategy for sustainable production in the Hexi Oasis region. The results of this study provide a theoretical basis for the establishment of a pumpkin water-saving planting technology system.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at Yimin Irrigation Experimental Station of Minle County, Gansu Province of China in 2020 and 2021. The research site is located at 38°39′ N, 100°43′ E, and 1970 m a.s.l. The region has a typical arid continental arid climate, with plenty of sunshine and a wide temperature variation. From 2000 to 2018, the annual mean air temperature and the average annual precipitation were 6.0 °C and 328 mm, respectively. The soil is characterized as a light loam of moderate fertility, and a pH value of 7.22. The soil field capacity is 24.0% (mass moisture content). The water table is about 20 m, and the irrigation area is not affected by salinization. The temperature and precipitation during the two crop growing seasons are shown in Figure 1. The total growing period precipitation was 176 mm in 2020, and 102.5 mm in 2021. The mean air temperature of the growing period was 17.27 °C in 2020, and 17.60 °C in 2021.

2.2. Experimental Design

The pumpkin variety "Tianmi" was provided by Wuwei Dadi Industry Co., Ltd., Wuwei, China. Pumpkin seeds were sown on 1 May 2020 and 2 May 2021. In the first year, harvest was performed on 20 August 2020 and on 21 August 2021 in the second year. Seeds were sown between 200 cm row spacing and 50 cm on-row plant spacing and plants were watered by a drip irrigation system (Figure 2), in which the dropper spacing and the dropper flow were 30 cm and 2.0 L/h, respectively. The field trial was conducted in a completely randomized blocks design with 3 replications and 27 plots, each experimental plot covered 15.4 m^2 (2.2 m × 7 m), and the total planting area was 415.8 m^2. A row of pumpkins was coated with a white plastic film (70 cm wide, 0.08 mm thick), and two rows were planted in each plot. The planting density was 17,532 plants/ha. There were three gradients of soil water deficit: adequate water supply (F, 75–85% in field capacity), light water deficit (L, 65–75% in field capacity), and moderate water deficit (M, 55–65% in field capacity). There were four growth stages of pumpkin: seedling (46 days), vine extension (24 days), fruit expansion (25 days), and maturation stages (14 days). The effective pumpkin root depth was taken as 60 cm [34]. The experimental treatments were listed in Table 1.

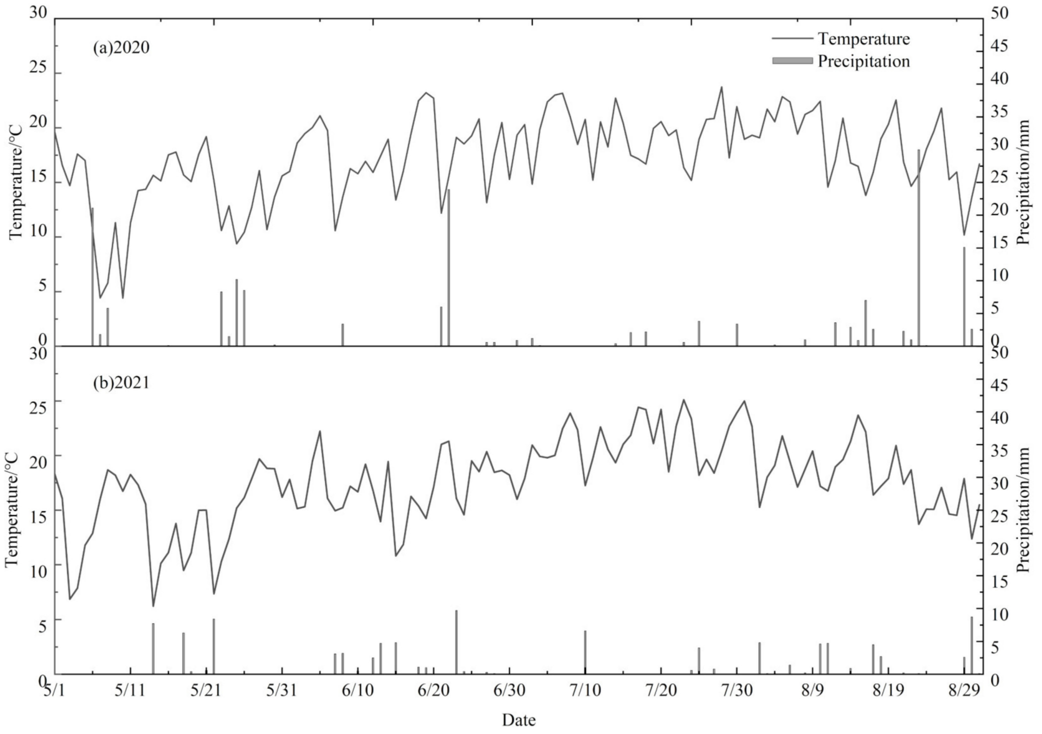

Figure 1. Dynamics of temperature and rainfall during the pumpkin growing seasons: (**a**) 2020; (**b**) 2021.

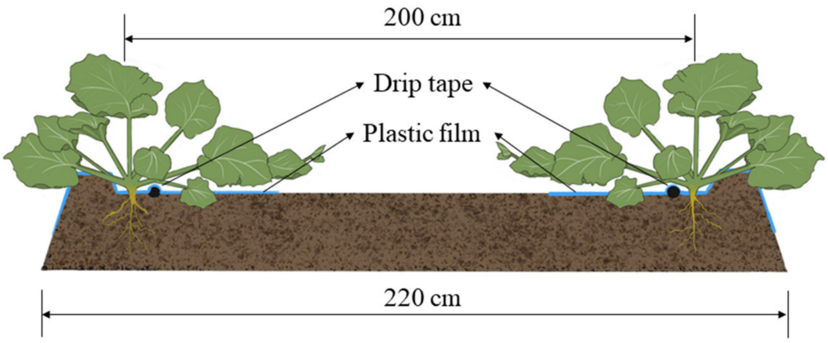

Figure 2. Planting diagram.

Table 1. Experimental design.

Treatment	Water Deficit Timing	Water Deficit Severity	Seedling Stage	Vine Extension Stage	Fruit Expansion Stage	Maturation Stage
CK	N/A	None	75–~85%	75–85%	75–85%	75–85%
LFFF	Seedling stage	Light	65–75%	75–85%	75–85%	75–85%
FLFF	Vine extension stage	Light	75–85%	65–75%	75–85%	75–85%
FFLF	Fruit expansion stage	Light	75–85%	75–85%	65–75%	75–85%
FFFL	Maturation stage	Light	75–85%	75–85%	75–85%	65–75%
MFFF	Seedling stage	Moderate	55–65%	75–85%	75–85%	75–85%
FMFF	Vine extension stage	Moderate	75–85%	55–65%	75–85%	75–85%
FFMF	Fruit expansion stage	Moderate	75–85%	75–85%	55–65%	75–85%
FFFM	Maturation stage	Moderate	75–85%	75–85%	75–85%	55–65%

2.3. Field Management

To ensure crop production, the experimental area was deep plowed 40 cm before sowing. Weeds were removed manually during planting. As a base fertilizer, 750 kg/ha ammonium nitrate fertilizer, 1125 kg/ha potassium sulfate, and 750 kg/ha superphosphate fertilizer were applied once at sowing.

2.4. Experimental Site

2.4.1. Pumpkin Growth Indexes

When it came time to harvest the pumpkins, 5 plants were chosen at random from each plot. A steel tape was used to measure the vine length (accuracy 0.1 cm), and a vernier caliper was used to measure the stem diameter (accuracy 0.02 mm).

2.4.2. Yield

Pumpkin yields were harvested and calculated for each plot after ripening, and the average yield of three replicate plots for each treatment was used for analysis. The pumpkins were weighed on an electronic scale (accuracy 0.01 g), and the yield was transformed to kg/ha.

2.4.3. Irrigation Amount

Irrigation should be performed immediately as the soil water content falls below the design lower limit, and the required irrigation amount should be determined using the irrigation quota equation [35]:

$$I = 10\rho bH\left(\theta_i - \theta_j\right) \tag{1}$$

where I refers to the irrigation amount (mm), ρb refers to the planned wetting layer soil bulk density (g/cm^3), H refers to the soil plan wet layer depth (cm), θ_i refers to the designed moisture content (the maximum relative moisture content of each treatment design target multiplied by the field water holding capacity), and θ_j refers to the moisture in the soil content before irrigation.

2.4.4. Water Consumption

Plant water consumption of each treatment is calculated by water balance equation [36]:

$$ET = 10\sum_{a=1}^{b} r_a h_a (SWC_{a1} - SWC_{a2}) + I + R \tag{2}$$

where ET(mm) means the crop evapotranspiration; b means the overall number of soil layers; r(g/cm^3) means the bulk density of the ath layer of soil; h means the thickness of the ath layer of soil; $SWC_{a1} - SWC_{a2}$ means the change in mass soil water content between two measurement dates (a1, a2), soil moisture in each treatment plot was measured every 7 days by soil drilling and drying weighing method. The soil sampling depth was 100 cm, which was divided into 5 parts: 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm, respectively; I means the amount of irrigation water (mm) during the growth period and R means the effective rainfall (mm) during the growth period.

2.4.5. Water Use Efficiency and Irrigation Water Use Efficiency

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were calculated using the following formulas [37]:

$$WUE = \frac{Y}{ET} \tag{3}$$

$$IWUE = \frac{Y}{I} \tag{4}$$

where WUE is the water use efficiency (kg/m^3); Y is the yield per unit area (kg/ha); ET is the crop evapotranspiration (m^3/ha); $IWUE$ is the irrigation water use efficiency (kg/m^3), and I is the irrigation volume per unit area (m^3/ha).

2.5. Quality

2.5.1. Quality Index

To determine the quality index, three pumpkin samples were obtained from each plot and replicated three times. Anthrone Colorimetry was used to determination of Soluble Sugar, and the NaOH titration method was used to determination of organic acid. Protein content was determined using the Coomassie Brilliant Blue G-250 method, the content of starch was used to determine enzymatic hydrolysis, and vitamin C was determined by 2,6-dichloroindophenol titration. A refractometer was used to determine the total soluble solid content (%) (ATAGO PAL-1, Atago, Tokyo, Japan).

2.5.2. Sugar-Acid Ratio

The sugar-acid ratio (SAT) was calculated using the following formulas [38]:

$$SAT = \frac{S}{A} \tag{5}$$

where SAT refers to the sugar-acid ratio, S refers to the soluble sugar content in pumpkin (g/100 g); A refers to the organic acid content in pumpkin (g/100 g).

2.6. Principal Component Analysis

The principal component score model and the comprehensive score model were calculated using the following formulas [39]

$$Y_n = P_1X_1 + P_2X_2 + \ldots + P_nX_n \tag{6}$$

$$F = W_1Y_1 + W_2Y_2 + \ldots + W_nY_n \tag{7}$$

where P_n represents eigenvectors of the corresponding matrix; X_n is the standardized indicator of the foxtail millet; Y_n is the score for each principal component of the foxtail millet; F is the comprehensive score of the foxtail millet; W_n is the nth principal component.

2.7. Statistical Analysis

All statistical analyses were performed on the data have used SPSS 25.0 (Stanford University) software. Significant variations between means were compared using Tukey's HSD test, and the principal component analysis (PCA) scores were used to evaluate the quality of pumpkin. The average value diagrams were created using Origin 2021 (Origin Lab). All analyses were conducted using two-year (2020 and 2021) averages.

3. Results

3.1. Effect of RDI on Pumpkin Traits at Harvest

3.1.1. Vine Length

Figure 3 demonstrates the effect of irrigation on pumpkin vine length using diverse water deficit gradients at different stages. Pumpkin vine length increased at a variable rate as the crop grew and developed. Specifically: vine extension stage > fruit expansion stage > maturation stage > seedling stage. Compared to CK, the vine lengths of LFFF and MFFF with water deficit at the seedling stage were decreased by 11.32% and 20.27%, respectively. Water deficit at the vine extension stage, the vine lengths were decreased by 17.85% and 29.83% for FLFF and FMFF. For the fruit expansion stage with water deficit, the vine lengths were decreased by 8.54% and 15.63% for FFLF and FFMF, while the vine lengths of FFFL and FFFM were reduced to 1.55% and 4.21% at the maturation stage with water deficit. When compared to CK, all treatments had different levels of vine length reduction at the end of growth. For light water deficit treatments (LFFF, FLFF, FFLF, FFFL), vine length was reduced by 1.10% to 4.23%, while for moderate water deficit treatments (MFFF, FMFF, FFMF, FFFM), vine length was reduced by 2.89% to 9.61%. Water deficit at the vine elongation stage was not conducive to the accumulation of vine length.

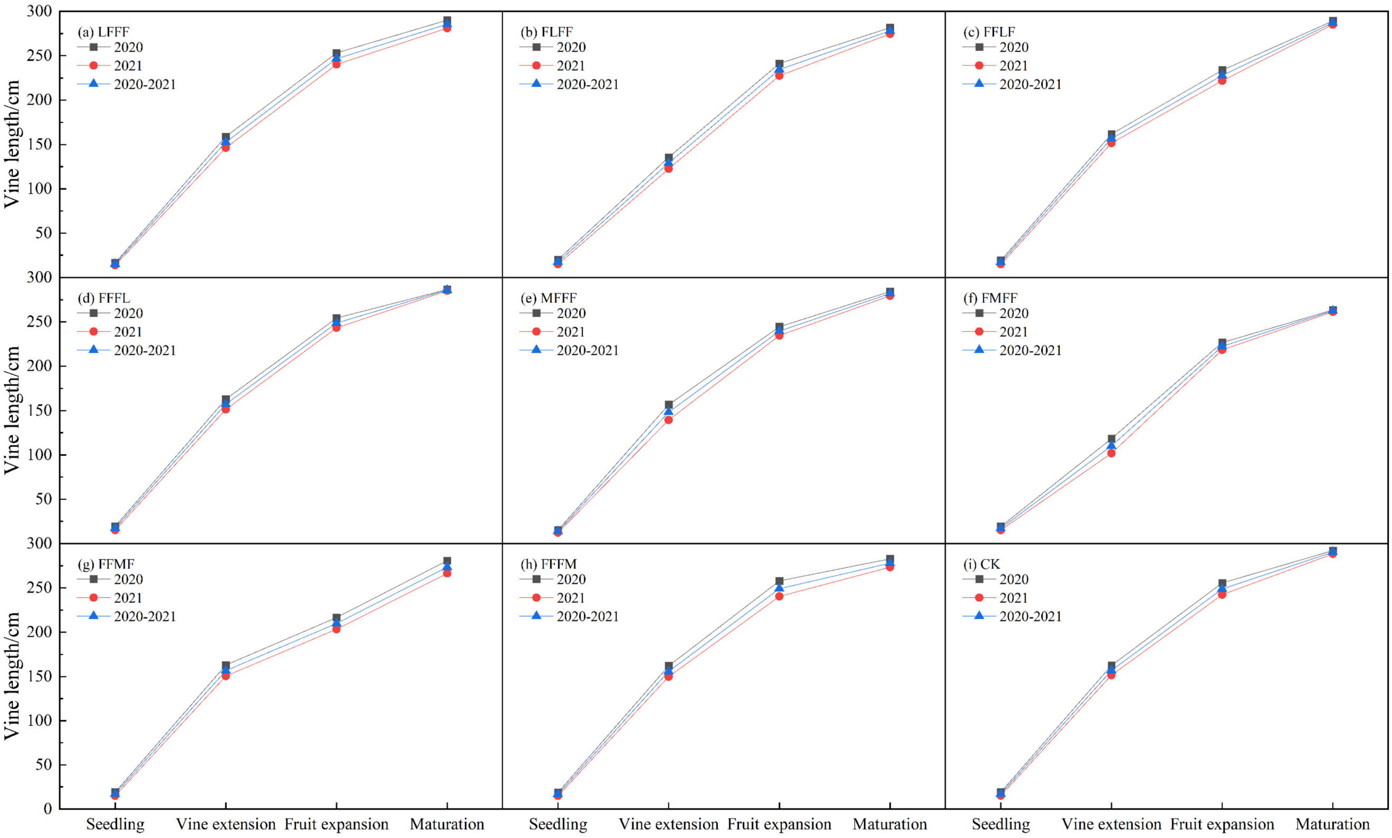

Figure 3. Effects of drip irrigation under mulch on the vine length of pumpkin.

3.1.2. Stem Thickness

The effects of different developmental stages on the stem thickness of pumpkin irrigated with different water deficit gradients can be seen in Figure 4. Pumpkin stem thickness increased at a variable rate as the crop grew and developed. Specifically: seedling stage > vine extension stage > fruit expansion stage > maturation stage. Compared to CK, the stem thickness of LFFF and MFFF with water deficit at the seedling stage was decreased by 12.68% and 19.15%, respectively. Water deficit at the vine extension stage, the stem thicknesses was decreased by 12.50% and 19.04% for FLFF and FMFF. For the fruit expansion stage with water deficit, the water deficit was decreased by 6.84% and 11.91% for FFLF and FFMF, while the stem thickness of FFFL and FFFM reduced to 2.26% and 5.05% at the maturation stage. All treatments showed various levels of stem thickness reduction at the end of the reproductive period compared to CK, ranging from 2.26% to 7.34% for the light water regulation deficit treatment and 5.05% to 11.78% for the moderate water regulation deficit treatment. When compared to CK, the treatments FLFF, FMFF, and FFLF, FFMF reduced pumpkin stem thickness accumulation by 7.34%, 11.78%, and 6.01%, 11.00%, respectively, indicating that water regulation deficits at vine extension and fruit expansion stages both significantly inhibited pumpkin stem thickness accumulation.

3.2. Yield

The reduction in water consumption caused by regulated deficit irrigation resulted in different degrees of reduction in pumpkin yield (Table 2), the yield of CK with adequate irrigation treatment was 46,708.57 kg/ha and the yield of moderate water regulation deficit treatment was 67.07% to 88.77% of CK. The yield of mild moisture regulation deficit treatment was 88.21% to 98.41% of CK; while LFFF had the least effect on yield at 45,966.90 kg/ha with no significant difference ($p > 0.05$); FFMF significantly reduced yield at 31,325.16 kg/ha. Moreover, the yield reduction in the moderate water deficit treatment was greater than that in the light water deficit treatment.

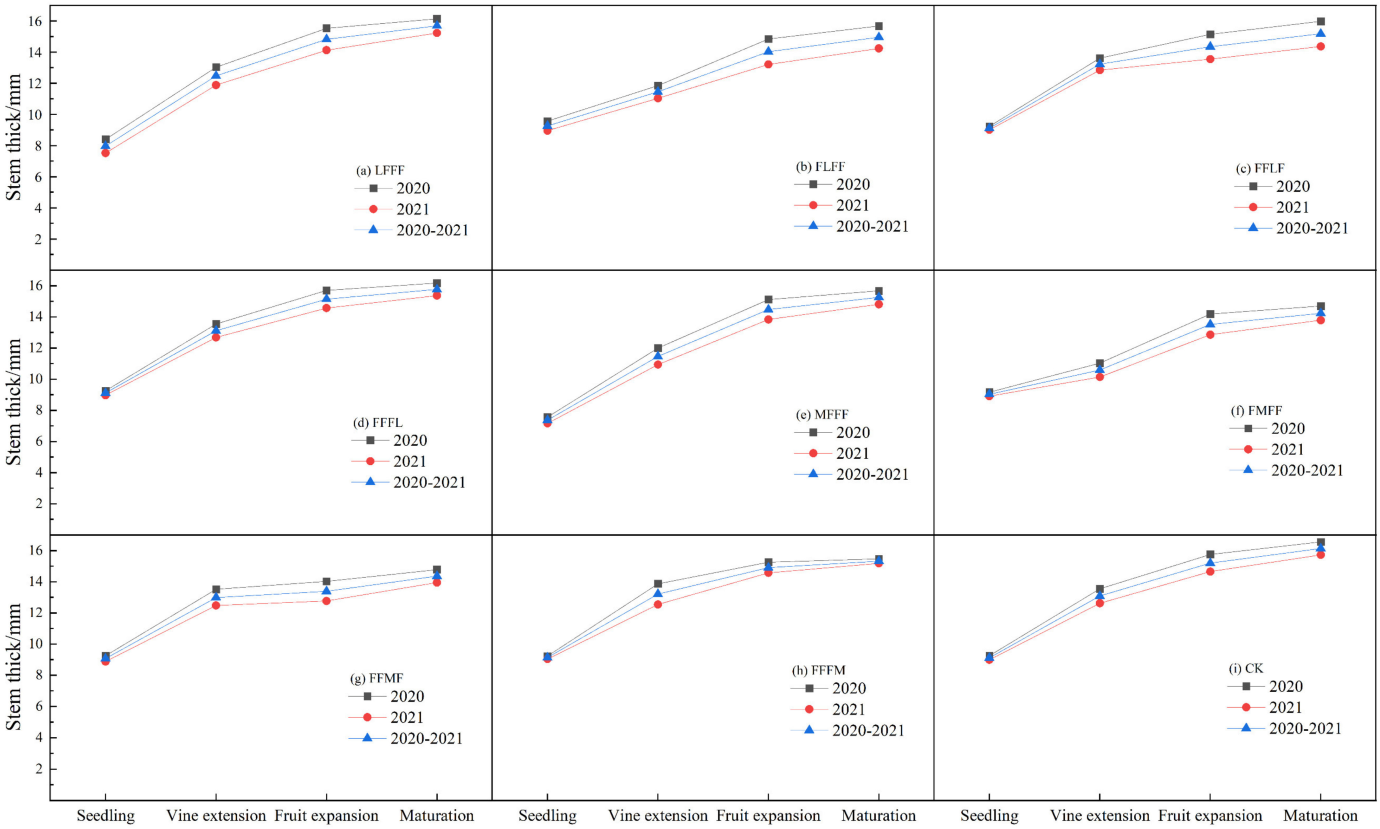

Figure 4. Effects of drip irrigation under mulch on the stem thickness of pumpkin.

3.3. Water Consumption, WUE and IWUE

3.3.1. Water Consumption

The water consumption, yield, WUE, and IWUE values of different regulated deficit irrigation treatments are provided in Table 2. In this study, the highest water consumption was in the fully irrigated treatment CK, reaching 4084.18 m^3/ha. In different stages of development water regulation deficit significantly reduced water consumption of pumpkin ($p < 0.05$), and water consumption ranged from 3116.87–3742.41 m^3/ha. The water consumption during the whole reproductive period of the moderate water loss treatment was reduced by 15.29%, 19.60%, 23.68%, and 14.35% compared with CK, while the water consumption during the whole reproductive period of the light water deficit treatments LFFF, FLFF, FFLF, FFFL were reduced by 9.73%, 5.37%, 13.96%, and 10.63% compared with CK, respectively. In particular, FFMF with moderate moisture deficit treatment has the largest reduction in water consumption in the two-year average, with 3116.87 m^3/ha; FLFF with light moisture deficit treatment has the smallest reduction in water consumption in the two-year average, with 3742.41 m^3/ha.

3.3.2. WUE

At each development stage of pumpkin, different water deficit irrigation strategies had various impacts on WUE. The WUE of LFFF with mild moisture deficit treatment was 12.47 kg/m^3, which was significantly higher than CK by 9.02%; FMFF and FFMF with moderate moisture deficit treatment reduced the WUE by 4.52% and 12.03% compared to

CK, respectively. In contrast, all other moisture treatments increased WUE compared to CK but not significantly, with increases ranging from 0.68% to 7.36%.

Table 2. Effects of different deficit irrigation treatments on water consumption, yield, water use efficiency and irrigation water use efficiency of pumpkin.

Year	Treatment	Irrigation Volume	Water Consumption	Yield	Water Use Efficiency	Irrigation Water Use Efficiency
		($m^3 \cdot ha^{-1}$)	($m^3 \cdot ha^{-1}$)	($kg \cdot ha^{-1}$)	($kg \cdot m^{-3}$)	($kg \cdot m^{-3}$)
2020	CK	2568.79 ^{a}	4049.72 ^{a}	46,266.90 ^{a}	11.42b ^{c}	18.01 ^{e}
	LFFF	2180.14 ^{bc}	3643.81 ^{ab}	45,066.89 ^{ab}	12.37 ^{a}	20.67 ^{ab}
	FLFF	2359.83 ^{ab}	3687.75 ^{ab}	42,900.21 ^{bc}	11.63 ^{ab}	18.18 ^{de}
	FFLF	2095.08 ^{bcd}	3502.99 ^{bc}	41,200.21 ^{c}	11.76 ^{ab}	19.67 ^{bcd}
	FFFL	2204.47 ^{b}	3647.57 ^{ab}	43,900.22 ^{abc}	12.04 ^{ab}	19.91 ^{bc}
	MFFF	2085.08 ^{bcd}	3492.99 ^{bc}	41,266.87 ^{c}	11.81 ^{ab}	19.79 ^{bc}
	FMFF	1804.65 ^{de}	3205.06 ^{c}	34,300.17 ^{d}	10.70 ^{cd}	19.01 ^{cde}
	FFMF	1639.46 ^{e}	3053.21 ^{c}	32,250.16 ^{d}	10.56 ^{d}	19.67 ^{bcd}
	FFFM	1885.16 ^{cde}	3522.72 ^{b}	41,400.21 ^{c}	11.75 ^{ab}	21.96 ^{a}
2021	CK	3235.77 ^{a}	4118.64 ^{a}	47,150.24 ^{a}	11.45 ^{b}	14.57 ^{e}
	LFFF	2619.76 ^{c}	3729.39 ^{bc}	46,866.90 ^{a}	12.57 ^{a}	17.89 ^{b}
	FLFF	2998.66 ^{b}	3797.07 ^{b}	43,266.88 ^{bc}	11.39 ^{b}	14.43 ^{e}
	FFLF	2575.37 ^{c}	3524.74 ^{cde}	41,200.21 ^{c}	11.69 ^{ab}	16.00 ^{d}
	FFFL	2804.92 ^{bc}	3652.41 ^{bcd}	45,733.56 ^{ab}	12.52 ^{a}	16.30 ^{cd}
	MFFF	2316.95 ^{d}	3426.16 ^{def}	40,500.20 ^{c}	11.82 ^{ab}	17.48 ^{bc}
	FMFF	2284.00 ^{d}	3362.43 ^{def}	37,450.19 ^{d}	11.14 ^{b}	16.40 ^{cd}
	FFMF	1932.87 ^{e}	3180.53 ^{f}	30,400.15 ^{e}	9.56 ^{d}	15.73 ^{d}
	FFFM	1975.52 ^{e}	3473.86 ^{cde}	41,530.21 ^{c}	11.96 ^{ab}	21.02 ^{a}
Average	CK	2902.28 ^{a}	4084.18 ^{a}	46,708.57 ^{a}	11.44 ^{bc}	16.29 ^{d}
	LFFF	2399.95 ^{cd}	3686.60 ^{b}	45,966.90 ^{ab}	12.47 ^{a}	19.28 ^{b}
	FLFF	2679.24 ^{ab}	3742.41 ^{b}	43,083.55 ^{bc}	11.51 ^{bc}	16.30 ^{d}
	FFLF	2335.22 ^{cd}	3513.87 ^{bc}	41,200.21 ^{c}	11.73 ^{abc}	17.83 ^{c}
	FFFL	2504.69 ^{bc}	3649.99 ^{b}	44,816.89 ^{ab}	12.28 ^{ab}	18.11 ^{bc}
	MFFF	2201.01 ^{de}	3459.57 ^{bc}	40,883.54 ^{c}	11.82 ^{ab}	18.64 ^{bc}
	FMFF	2044.32 ^{ef}	3283.74 ^{cd}	35,875.18 ^{d}	10.92 ^{c}	17.70 ^{c}
	FFMF	1786.16 ^{f}	3116.87 ^{d}	31,325.16 ^{e}	10.06 ^{d}	17.70 ^{c}
	FFFM	1930.34 ^{f}	3498.29 ^{bc}	41,465.21 ^{c}	11.85 ^{ab}	21.49 ^{a}

Note: Different lowercase letters within a column indicate a significant difference among treatments at $p < 0.05$ for the same year.

3.3.3. IWUE

IWUE was increased at all stages of pumpkin development, with IWUE increased by 0.07% to 18.35% for mild water stress treatments and 8.64% to 31.92% for moderate water stress treatments compared to CK. In this case, deficit regulation at the seedling and maturation stages is beneficial to improve IWUE. Compared to CK, FFFM was significantly higher by 31.92% in the moderate water deficit treatment at the maturation stage. The effect of deficit regulation at vine extension and maturation stages was less on improving IWUE, where FLFF was only 0.08% higher in the light water deficit treatment at vine extension stage compared to CK. As with WUE, water regulation deficit at the seedling and maturation stages were more beneficial to improving pumpkin IWUE.

3.4. *Pumpkin Quality*

3.4.1. Quality

Table 3 shows the different effects of regulated deficit irrigation under mulched on pumpkin quality. Water deficit treatment at the seedling stage has no significant effect on soluble sugars compared to CK, while water deficit treatment at fruit expansion and maturation stages increased soluble sugars by 2.31% to 13.87%. The organic acid of LFFF was 0.21 g/100 g in the light water regulation deficit treatment at the seedling stage, which was 5.25% lower than that of CK. While compared to CK, all other treatments rose to various extents, ranging from 2.97% to 18.95%, in which the effect of treatment FFFM was the most significant. Both light and moderate water deficit treatments increased protein content in pumpkin by 3.14% to 45.03%, and moisture water deficit treatment at the fruit expansion and maturation stages were more favorable to increase protein content. MFFF in moderate water deficit treatment at the seedling stage was disadvantageous to vitamin C accumulation, decreasing by 3.42% compared to CK, while all other treatments increased vitamin C content by 1.97% to 18.77%. Soluble solids in FMFF decreased by 2.96% compared to CK in the moderate water deficit treatment, while all other treatments increased soluble solids content by 0.29% to 28.15%. The moderate water deficit treatment LFFF and the moderate water deficit treatment FFMF improved the sugar-acid ratio of pumpkin by 5.96% and 2.89% compared with CK, respectively. All other treatments reduced the sugar-acid ratio of pumpkin by 3.98% to 11.98%, with treatment FMFF reducing it most obviously.

Table 3. Effects of different deficit irrigation treatments on qualities of pumpkin.

Years	**Treatment**	**Soluble Sugar**	**Organic Acid**	**Protein**	**Vitamin C**	**Soluble Solids**	**Ratio of Sugar to Acid**
		(g/100 g)	**(g/100 g)**	**(g/100 g)**	**(mg/100 g)**	**(%)**	
2020	CK	7.81 ^{de}	0.21 ^{cd}	1.06 ^{e}	21.03 ^{de}	10.61 ^{cd}	37.99 ^{ab}
	LFFF	7.78 ^{de}	0.20 ^{d}	1.12 ^{de}	21.77 ^{cd}	11.24 ^{c}	39.20 ^{ab}
	FLFF	7.80 ^{de}	0.21 ^{bcd}	1.03 ^{e}	21.28 ^{de}	10.75 ^{cd}	36.45 ^{a}
	FFLF	8.12 ^{cd}	0.23 ^{bc}	1.32 ^{ab}	23.82 ^{b}	11.42 ^{d}	36.03 ^{ab}
	FFFL	8.31 ^{bc}	0.23 ^{ab}	1.33 ^{ab}	22.36 ^{c}	12.49 ^{b}	36.06 ^{ab}
	MFFF	7.62 ^{e}	0.22 ^{bcd}	1.23 ^{bc}	20.33 ^{e}	11.23 ^{c}	34.76 ^{ab}
	FMFF	7.61 ^{e}	0.22 ^{bcd}	1.15 ^{cd}	22.36 ^{c}	10.22 ^{d}	34.83 ^{b}
	FFMF	8.68 ^{ab}	0.23 ^{ab}	1.37 ^{a}	24.09 ^{ab}	13.08 ^{ab}	38.11 ^{ab}
	FFFM	8.89 ^{a}	0.25 ^{a}	1.41 ^{a}	24.91 ^{a}	13.58 ^{a}	35.86 ^{b}
2021	CK	6.47 ^{c}	0.23 ^{cd}	0.85 ^{d}	19.57 ^{d}	10.35 ^{e}	27.87 ^{ab}
	LFFF	6.54 ^{c}	0.22 ^{d}	1.08 ^{bc}	20.11 ^{cd}	10.79 ^{de}	30.39 ^{a}
	FLFF	6.31 ^{cd}	0.24 ^{bcd}	0.96 ^{cd}	20.12 ^{cd}	10.27 ^{e}	26.68 ^{bc}
	FFLF	6.49 ^{c}	0.24 ^{bc}	1.22 ^{ab}	22.43 ^{ab}	11.87 ^{bc}	26.71 ^{bc}
	FFFL	6.86 ^{b}	0.26 ^{abc}	1.33 ^{a}	21.62 ^{bc}	12.43 ^{b}	26.66 ^{bc}
	MFFF	6.29 ^{cd}	0.24 ^{bcd}	1.01 ^{c}	18.88 ^{d}	11.38 ^{cd}	26.86 ^{b}
	FMFF	6.12 ^{d}	0.26 ^{ab}	0.82 ^{d}	22.13 ^{ab}	10.12 ^{e}	23.59 ^{c}
	FFMF	7.11 ^{ab}	0.24 ^{bc}	1.28 ^{a}	21.43 ^{bc}	12.41 ^{b}	29.37 ^{ab}
	FFFM	7.37 ^{a}	0.27 ^{a}	1.36 ^{a}	23.31 ^{a}	13.28 ^{a}	26.93 ^{b}
Average	CK	7.14 ^{de}	0.22 ^{de}	0.96 ^{d}	20.30 ^{de}	10.48 ^{de}	32.62 ^{ab}
	LFFF	7.16 ^{de}	0.21 ^{e}	1.10 ^{c}	20.94 ^{d}	11.02 ^{cd}	34.56 ^{a}
	FLFF	7.06 ^{de}	0.23 ^{cd}	1.00 ^{d}	20.70 ^{d}	10.51 ^{de}	31.32 ^{b}
	FFLF	7.31 ^{cd}	0.23 ^{bc}	1.27 ^{b}	23.13 ^{b}	11.65 ^{c}	31.16 ^{b}
	FFFL	7.59 ^{bc}	0.24 ^{b}	1.33 ^{ab}	21.99 ^{c}	12.46 ^{b}	31.05 ^{b}
	MFFF	6.96 ^{e}	0.23 ^{cd}	1.12 ^{c}	19.61 ^{e}	11.31 ^{c}	30.66 ^{bc}
	FMFF	6.87 ^{e}	0.24 ^{bc}	0.99 ^{d}	22.25 ^{bc}	10.17 ^{e}	28.71 ^{c}
	FFMF	7.90 ^{ab}	0.24 ^{bc}	1.33 ^{ab}	22.76 ^{bc}	12.75 ^{b}	33.56 ^{a}
	FFFM	8.13 ^{a}	0.26 ^{a}	1.39 ^{a}	24.11 ^{a}	13.43 ^{a}	31.13 ^{b}

Note: Different lowercase letters within a column indicate a significant difference among treatments at $p < 0.05$ for the same year.

3.4.2. Principal Component Analysis

Six quality indexes including soluble sugar (X_1), organic acid (X_2), protein(X_3), vitamin C (X_4), Soluble solids (X_5), and Ratio of sugar to acid (X_6) were selected for principal component analysis, and factor loading and variance contribution rate (Table 4) were obtained.

Table 4. Factor loadings and variance contribution rates of the principal components.

Indicator Variables	**Factor Loading**	
	Primary Principal Component	**Secondary Principal Component**
Soluble sugar X_1	0.935	0.276
Organic acid X_2	0.846	−0.507
Protein X_3	0.939	0.156
Vitamin C X_4	0.857	−0.204
Soluble solids X_5	0.951	0.211
Ratio of sugar to acid X_6	−0.001	0.989
Characteristic values	4.112	1.421
Variance contribution/%	68.529	23.683
Cumulative/% contribution rates/%	68.529	92.212

After extraction, the eigenvalues of the first 2 principal components were greater than 1, and the cumulative contribution rate reached 92.212%, indicating that the two principal components contained most of the information of six indicators, which could be used to evaluate the quality of pumpkin. The primary principal component explained 68.529% of the total variation information, mainly reflecting the effects of five indicators: soluble solids (X_5), protein (X_3), soluble sugar (X_1), vitamin C (X_4), and organic acid (X_2). The secondary principal component contained 23.683% of the total variation information, mainly reflecting the influence of the ratio of sugar to acid (X_6).

We establish the principal component score model and the comprehensive score model for the ratio of the 2 principal components to the eigenvalues by Formulas (6) and (7):

$$Y_1 = 0.227\ X_1 + 0.206\ X_2 + 0.228\ X_3 + 0.280\ X_4 + 0.231\ X_5 + 0.000\ X_6 \tag{8}$$

$$Y_2 = 0.194\ X_1 - 0.357\ X_2 + 0.110\ X_3 - 0.144\ X_4 + 0.149\ X_5 + 0.696\ X_6 \tag{9}$$

$$F = 0.7432Y_1 + 0.2568Y_2 \tag{10}$$

By calculating the quality scores of CK and each water deficit treatment, the scores were ranked according to the comprehensive scores (Table 5). Among them, the quality of pumpkin treated with a moderate deficit at maturity was the best, and the quality of pumpkin treated with a moderate deficit at the vine extension stage was the worst. According to the principal component analysis, the principal component components values were ranked as FFFM > FFMF > FFFL > FFLF > LFFF > MFFF > CK > FLFF > FMFF. At the vine extension stage, the comprehensive quality of water deficit treatment was worse than that of CK, and the comprehensive quality of water deficit treatment at the fruit expansion, maturation, and seedling stages were higher than that of CK.

Table 5. Comprehensive evaluation of quality traits of pumpkins in different deficit irrigation treatments.

Treatments	**Composite Scores**	**Comprehensive Ranking**
CK	−0.62	7
LFFF	−0.11	5
FLFF	−0.69	8
FFLF	0.19	4
FFFL	0.50	3
MFFF	−0.59	6
FMFF	−0.94	9
FFMF	0.98	2
FFFM	1.27	1

3.5. Relationship between Related Indexes

3.5.1. Relationship between Yield and WUE

As shown in Figure 5, the relationship between pumpkin yield and WUE throughout the reproductive period in this study was a quadratic parabolic relationship, with a variation curve of: $y = -8.974 \times 10^{-9} x^2 + 8.275 \times 10^{-4} x - 7.105$ ($R^2 = 0.808$), where y is the water use efficiency (kg/m^3), and x is the pumpkin yield (kg/ha). WUE increased as yield increased until it reached a critical point, at which point it decreased as yield increased, and that was not favorable to pumpkin in terms of enhancing WUE and achieving high yield while saving water.

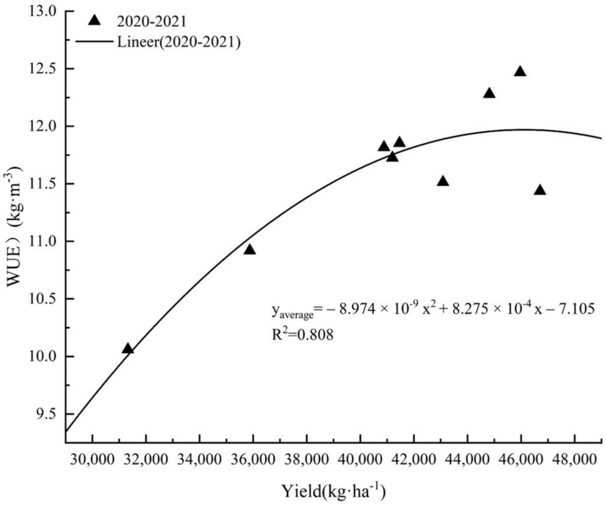

Figure 5. Relationship between yield and water use efficiency of pumpkins.

3.5.2. Relationship between Water Consumption and Yield

Figure 6 showed that the water consumption and yield of pumpkin in this study had a quadratic parabolic relationship during the overall growth period, with the variation curve being: $y = -0.019 x^2 + 150.171 x - 25{,}5821.707$ ($R^2 = 0.961$), where y is pumpkin yield (kg/ha), and x is water consumption (m^3/ha). The yield tends to increase as water consumption increases, until reaching the critical point.

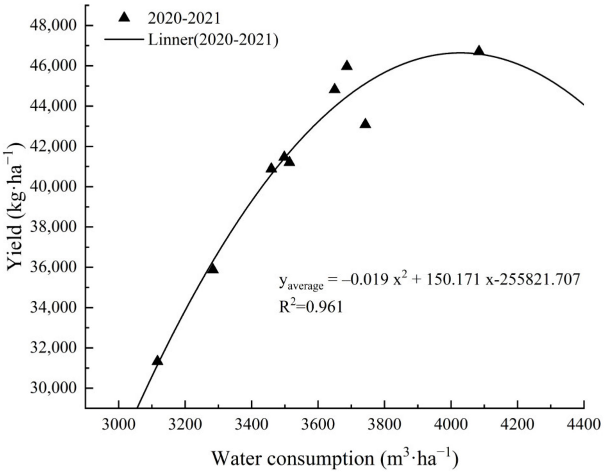

Figure 6. Relationship between consumption and yield of pumpkins.

3.5.3. Relationship between Water Consumption and IWUE

According to Figure 7, the quadratic parabolic relationship between water consumption and IWUE for pumpkin during the whole reproductive period in this study is: $y = -7.721 \times 10^{-6} X^2 + 0.054 x - 74.869$ ($R^2 = 0.320$), where y is pumpkin irrigation water use efficiency (kg/m^3), and x is water consumption (m^3/ha). As shown in the figure, the IWUE increases as the water consumption of pumpkin increases, reaching a maximum of 21.49 kg/ha when water consumption rises to 3498.29 m^3/ha. However, a continuous increase in water consumption leads to a decrease in IWUE.

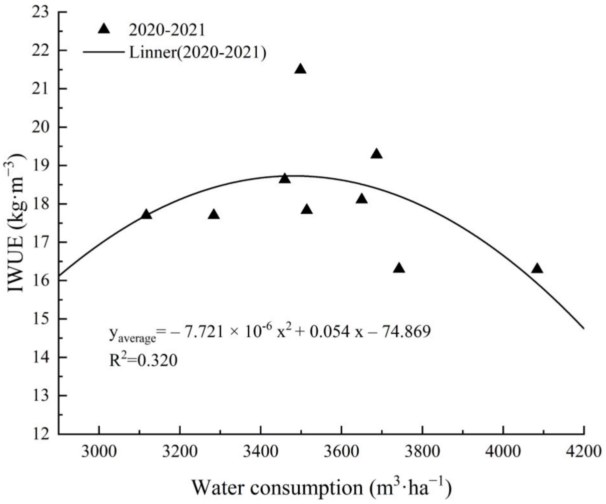

Figure 7. Relationship between water consumption and IWUE of pumpkins.

4. Discussion

Drip irrigation under mulch not only reduces inefficient evaporation of soil water [40] but also improves the soil environment [41,42]. When the soil moisture conditions change, it will affect the growth of crops [43,44], so that timely and appropriate water deficit regulation can be carried out, the physiological metabolism of crops may be changed, and stable yield and water saving quality can be achieved [45,46]. The vine length and stem thickness of pumpkin decreased by 1.10%, 9.61%, and 2.26%, 11.78% compared to CK, respectively, in which deficit regulation at the vine extension stage and fruit expansion stage had a greater impact on growth indexes, so these two periods were highly sensitive to water stress; while deficit regulation at the seedling stage and maturation stage had less impact on growth indexes. Such results are consistent with studies in watermelon [47,48], melon [49], and pumpkin [50] where water deficiency during water-sensitive periods affects the accumulation of growth indicators, which in turn affects crop yield and quality [48,51].

In the present study, the water consumption and yield of CK were the largest with 4084.18 m^3/ha and 46,708.57 kg/ha. Pumpkin water consumption and yield were reduced to different degrees in RDI, ranging from 8.37% to 23.68% and 1.59% to 32.93%, respectively, and the reduction in water consumption led to a significant reduction in yield [52,53]. Light water deficit at the seedling stage had less effect on yield, which was 45,966.90 kg/ha, only 1.59% lower than CK, caused by the root system in slow growth period at the seedling stage, root vigor is weak, appropriate water deficit is beneficial to root growth and improve crop drought resistance, and the effect on yield is not significant [35]. Since pumpkin starts to enter the reproductive growth period at the fruit expansion stage, it is very sensitive to water stress, where water deficiency inhibits photosynthesis and transpiration of the crop, and the rehydration compensation effect is not obvious, thus leading to serious yield reduction [47]. This is different from previous research, deficit water during the fruit ripening stage of watermelon had little influence on yield while irrigation water use efficiency decreased to a lesser extent [48], and may be related to the different timing and extent of water deficit regulation, and test conditions.

In this study, it was found that the highest WUE and IWUE were achieved by light water deficit at the seedling stage with 9.02% and 18.34% increase compared to CK, respectively, and compared to CK, WUE and IWUE at the maturation stage with light water deficit were increased by 7.36% and 11.16%, respectively. It can be seen that appropriate water deficit at seedling and maturation stages is beneficial to the improvement of WUE and IWUE, which is in accordance with the study of EI-Mageed that squash had the highest WUE at I85%IWA but non-significant yield reduction [54]. There are currently few studies on water deficit in pumpkin around the world, particularly on the impacts of water deficit on growth, yield, and quality at various developmental stages, and more research is needed to develop effective water management measures.

Previous studies have shown that appropriate water regulation deficit can also improve fruit quality, Zheng showed that small watermelon with light water deficit during the fruit expansion stage increased soluble sugar content by 17.79%–19.68% compared to the control, which was beneficial to improving watermelon quality [55], and crop quality, as an important indicator of crop nutrition, determines the nutritional value and taste of the crop. It is found in this study that the soluble sugar, protein, vitamin C, and soluble solids contents of pumpkin can be significantly increased with the reduction of irrigation during the fruit expansion and maturation periods, while adequate water supply will have a diluting effect on nutritional indicators such as soluble solids by absorbing large amounts of water at fruit maturation [56], resulting in lower fruit quality. Fruit's good taste requires a high sugar-acid ratio at the proper sugar-acid ratio [38]. This study showed that light water deficit at the seedling stage and moderate water deficit at the fruit expansion stage could improve the sugar-acid ratio of fruits. In order to comprehensively reflect the quality of pumpkin under different deficit irrigation conditions, we comprehensively analyzed and evaluated the quality indicators of pumpkin. Principal component analysis (PCA) is a multivariate statistical method to investigate the correlation between multiple variables. Through the idea of dimension reduction, multiple related variables are transformed into unrelated comprehensive indicators for evaluation. It is widely used in many fields [57,58]. After the comprehensive quality analysis and ranking by principal component analysis, the best quality of pumpkin was obtained by moderate water stress at the fruit expansion stage, and the worst quality was obtained by moderate water stress at the vine extension stage.

5. Conclusions

This trial examined the impact of drip irrigation under mulch on pumpkin growth, yield, quality, and water use efficiency. The following conclusions were reached: (1) The water deficit reduced pumpkin water consumption, resulting in varying degrees of reduction in growth index and yield, and the light water deficit at the seedling stage could effectively improve the water use efficiency (12.47 kg/m^3) without significantly affecting the yield (45,966.90 kg/ha). (2) Suitable water deficit regulation can improve pumpkin fruit soluble sugar, organic acid, vitamin C, protein, and soluble solids content. Furthermore, the fruits with light water deficit (65%~75% in field capacity) at the seedling stage and at the maturation stage with moderate water deficit (55%~65% in field capacity) had a higher sugar-acid ratio for better taste. Therefore, integrating crop growth, yield, water use efficiency, irrigation water use efficiency, quality, and overall ranking, the study concluded that the light water deficit treatment at the seedling stage and adequate irrigation at other growth stages was the optimal irrigation strategy for pumpkin in the Hexi Oasis region. More data from different years and locations would be needed to prove the method's generality and applicability in other regions. As a result, more research is needed to determine the impact of the quantity of water deficit and the stage at which the deficit occurs on the yield and quality of various varieties and regions.

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