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Effect of Water-Fertilizer Coupling on the Growth and Physiological Characteristics of Young Apple Trees

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Abstract: China has the largest apple-growing area and fresh fruit production in the world; however, water shortages and low fertilizer utilization rates have restricted agricultural development. It is a major challenge to obtain scientific and reasonable irrigation and fertilization systems for young apple trees in semi-arid regions of northern China. A 2-year field bucket experiment with four irrigation levels of W1 (75–90% Fs, where Fs is the field water holding capacity), W2 (65–80% Fs), W3 (55–70% Fs), and W4 (45–60% Fs), and three fertilizer levels of F1 (27-9-9 g N-P_2O_5-K_2O), F2 (18-9-9 g N-P_2O_5-K_2O), and F3 (9-9-9 g N-P_2O_5-K_2O) was conducted in 2019 and 2020, so as to explore the effects of different water and fertilizer treatments on the growth and physiological characteristics of young apple trees. The results showed that the plant growth, leaf area, and dry matter of young apple trees at each growing period reached maximum values under F1W2, and they showed a positive linear relationship with relative chlorophyll content (SPAD), net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption, and water use efficiency (WUE). With the growth of young apple trees, water-fertilizer coupling could significantly increase the leaf SPAD of young apple trees. Pn, Tr, and Gs reached the maximum value under F1W1, and although they decreased under F1W2, the water use efficiency increased by 2.3–25.7% and 4.0–23.8% under F1W2 compared with other treatments in two years, respectively. The water consumption of young apple trees increased with the increase of irrigation and fertilizer, and both dry matter and water productivity reached the maximum value under F1W2, which increased by 0.8%, 14.6% in 2019, and 0.6%, 11.1% in 2020 compared with F1W1, while water consumption decreased by 12.2% and 9.4% in both years. In conclusion, F1W2 treatment (soil moisture was controlled at 65–80% of field water holding capacity, and N-P_2O_5-K_2O was controlled at 27-9-9 g) was the best coupling mode of water and fertilizer for young apple trees in semi-arid areas of northern China.

Keywords: water-fertilizer coupling; dry matter; water productivity; photosynthetic characteristics; water use efficiency

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1. Introduction

Apples are the fourth most produced and consumed fruit in the world [1] and are widely used in the nutritional, food, and pharmaceutical industries due to their high nutritional value as they contain many minerals and vitamins [2]. In the 2019–20 production season, global apple production reached 7.5834×10^7 t. According to statistics, China is the largest country in the world in terms of apple planting area and fresh fruit production [3], and China's apple planting area in 2019 reached 2.086×10^6 ha, and the production reached 4.242×10^7 t [4]. In addition, apples are also one of the most important cash crops in

China, having a crucial role in helping farmers escape poverty, become rich, and effectively increase their income [5]. However, water shortages and low fertilizer utilization are the major constraints to apple production in China [6].

Water-saving irrigation is an effective technology for mitigating land drought stress and is important for promoting sustainable agricultural development [7]. In recent years, drip irrigation, as one of the main technologies for water-saving irrigation, has been successfully applied to greenhouse or field production with obvious water-saving and economic benefits [8–11]. Casamali et al. [12] showed through a study on the effect of different irrigation levels on peach growth and development that peach trees were more favorable under drip irrigation conditions than microspray irrigation. Jamshidi et al. [13] showed that mild deficit irrigation was beneficial in reducing the stomatal conductance of orange trees to maintain relatively constant leaf water potential for citrus production under drip irrigation conditions by studying the growth physiology of orange trees in a semi-arid climate in southern Iran through five irrigation levels. Bhatt et al. [14] found that height, diameter, the number of internodes, biomass yield, and sugarcane yield of sugarcane were increased under non-sufficient irrigation treatment compared to sufficient irrigation treatment, and a moderate reduction in irrigation was beneficial in increasing sugarcane and also helped in increasing sugarcane yield and reducing pest incidence. Crop water productivity (CWP) reflects the relationship between the output of a crop and its water consumption. Parvizi et al. [15] found that the application of mild deficit irrigation increased the CWP of pomegranate as compared to sufficient irrigation. In addition, water use efficiency (WUE), as an important measure of plant drought tolerance, depends on the coupled processes of photosynthesis and transpiration and can effectively respond to the water use strategy of crops [16]. Abdel-Sattar et al. [17] showed that moderate deficit irrigation is beneficial to increasing pomegranate yield, commercial fruit percentage, and WUE. However, what level of irrigation can promote the growth of young apple trees under drip irrigation conditions still needs further research and study.

In addition, irrigation, fertilizer is another critical factor that affects the growth and yield of apple trees. A reasonable application of fertilizer can effectively improve soil fertility, promote crop growth, and increase yield [18]. Quaggio et al. [19] showed through a study on the effect of water-fertilizer coupling on citrus that citrus was able to achieve maximum fruit yield using moderate levels of N and K fertilizer amounts. Peng et al. [20] showed that the use of deficit-regulated irrigation and moderate fertilizer application (103.2 kg ha^{-1}) during the mango mature period was effective in improving mango yield and water and fertilizer use efficiency. Wang et al. [11] reported that crop yield, vitamin C content, and water use efficiency increased with the increase in fertilizer application and that moderate fertilization was beneficial to promote potato growth. However, insufficient or excessive fertilization can adversely affect crop growth; excessive fertilization reduces apple yield, water use efficiency, and fruit quality [21]; insufficient fertilizer also inhibits crop growth by reducing photosynthetic characteristics and water use efficiency [22]. Therefore, the appropriate amount of fertilizer can ensure normal growth [23]. However, relatively few studies have been conducted on the effects of fertilizer application on the growth and development of young apple trees in semi-arid regions of northern China, and further research is needed on the effects of fertilizer application on the growth and development, photosynthetic characteristics, and water use efficiency of young apple trees.

Integrated drip irrigation and fertilization technology is today recognized as one of the best technologies to save irrigation and fertilizer as well as to improve the utilization of water and fertilizer resources [24–26]. To improve the efficiency of water and fertilizer utilization in apples, we must closely integrate irrigation and fertilization technologies, study the coupling relationship between water and nutrients, explore the response mechanisms of apples to different water and fertilizer supplies under water and fertilizer integration conditions, and seek the optimal water supply and fertilization mode and the best irrigation and fertilization system. In recent years, scholars at home and abroad have conducted some studies on the coupling effect of water and fertilizer on fruit trees, but mainly focused on mature fruit trees [27,28], and fewer studies on young fruit trees because it is difficult to reflect the final yield and economic benefits because young trees do not bear fruit, and it is more difficult to study. However, young trees are a crucial stage of fruit tree growth, which determines the future growth of fruit trees and the amount of fruit set.

Although China is the world's largest producer of apples, its per capita yield is relatively low due to low water and fertilizer use efficiency and a large population. In addition, the study on the synergistic effect of water-fertilizer integration on apple growth and development indexes in semi-arid areas of northern China under drip irrigation conditions is still in the preliminary exploration stage. Therefore, this study was based on the water and fertilizer regulation experiment for two consecutive years to explore the effects of water-fertilizer coupling on the growth and physiological characteristics of young apple trees and to determine a reasonable model of irrigation and fertilization for apples. The results of this study can provide a scientific basis for the irrigation and fertilization management of young apple trees in semi-arid regions of the north.

2. Materials and Methods

2.1. Experimental Site Description

A two-year (March 2019–October 2020) bucket experiment was carried out on young apple trees at the Agricultural Engineering Experiment Center in the semi-humid and semi-arid region of Henan University of Science and Technology, Luoyang, Henan, China (34°66′ N, 112°37′ E). This study area is characterized by a temperate monsoon climate with an altitude of 172 m. The four seasons of the year are distinct, with hot and rainy summers and cold and dry winters. The mean annual temperatures of 15.1 °C and 15.0 °C in 2019 and 2020, the mean annual sunshine time of 1941.1 h and 1880.5 h in 2019 and 2020, respectively, and the mean annual precipitation of 611.2 mm and 586.5 mm in 2019 and 2020 at the growth and development period of young apple trees (Figure 1), with precipitation mostly concentrated in June, July, and August, and the mean annual evaporation of 1200 mm The experiment was carried out in a bucket, and the experiment soil was cinnamon soil, which was naturally air-dried and broken up, passed through a 5 mm mesh sieve, and mixed well after removing impurities. Each bucket was filled with 30 kg of soil, with a filling capacity of 1.31 g cm^{-3}. The basic properties of the soil are shown in Table 1.

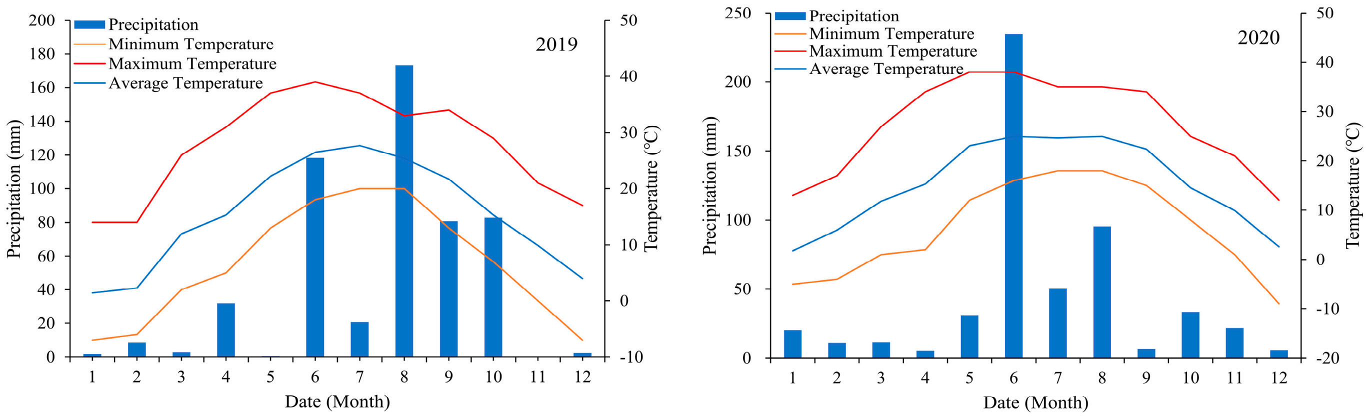

Figure 1. Daily rainfall and average temperature during the 2019 and 2020 in Luoyang.

2.2. Experimental Design

The experiment was conducted by drip irrigation with two factors of irrigation and fertilization, including four levels of irrigation and three levels of fertilization. Nitrogen, phosphorus, and potassium fertilizers used were urea, diammonium hydrogen phosphate, and potassium sulfate, respectively, and fertilizers were applied with water at one time. The experiment was conducted in a complete combination design with 12 treatments, with three replications of the experiment to measure data, and all treatment combinations were compared in a shelter. The experiment fruit trees were 4-year-old red Fuji apple trees (the base rootstock was yellow begonia). Approximately 36 young barrel-planted apple trees of the same growth, size, and health were selected each year, and the orchard was regularly controlled for pests and diseases. All young barrel-planted apple trees were subjected to the same agronomic measures such as fertilization, drip irrigation, pruning, insecticide spraying, and weeding, and their soil moisture content was controlled by the soil extraction and drying method (temporary shelters were built during rainfall). The experimental field layout is shown in Figure 2. Young apple trees were started with water and fertilizer treatments on 20 March 2019 and 21 March 2020, and the design of the experimental irrigation and fertilizer application amounts is shown in Table 2.

Table 1. Basic physicochemical properties of topsoil at the experimental field.

Soil Property	Value
Soil texture	cinnamon soil
Soil organic matter	12.6 g kg^{-1}
Nitrate nitrogen	16.4 mg kg^{-1}
Ammonium nitrogen	8.3 mg kg^{-1}
Total nitrogen	1.0 g kg^{-1}
Available nitrogen	58.6 mg kg^{-1}
Available phosphorus	13.2 mg kg^{-1}
Available potassium	198 mg kg^{-1}
Field capacity	24.1%
PH	8.03

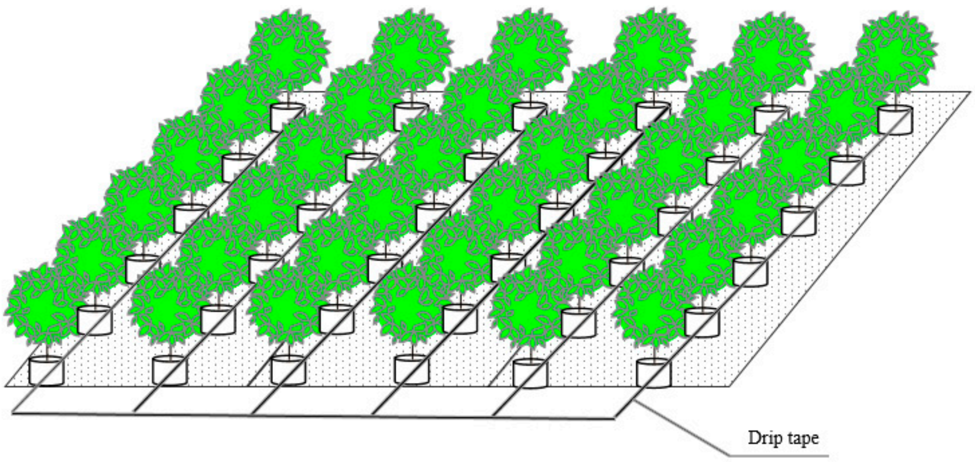

Figure 2. Layout of apple drip irrigation tapes and soil sampling locations in relation to plant row spacing.

Table 2. Design of irrigation and fertilizer application rates for a two-year experiment of young apple trees.

Fertilizer Treatment ($N-P_2O_5-K_2O$)		Irrigation Treatment			
		W1	W2	W3	W4
F1	27-9-9 g	75~90% Fs	65~80% Fs	55~70% Fs	45~60% Fs
F2	18-9-9 g				
F3	9-9-9 g				

Note: Fs is field water holding capacity. W1, W2, W3, and W4: four irrigation levels, in order of sufficient irrigation, mild deficit, moderate deficit, and severe deficit; F1, F2, and F3: three fertilization levels, in order of high, medium, and low levels of fertilization.

Young apple trees in 2019 will have the following growing periods: budding and flowering stage (20 March–18 April), shoot growth stage (19 April–18 May), fruit-setting and expansion stage (19 May–17 June), and mature period (18 June–17 July). Young apple trees in 2020 have the following growing periods: budding and flowering (21 March–19 April), shoot growth stage (20 April–19 May), fruit-setting and expansion stage (20 May–18 June), and mature period (19 June–18 July).

2.3. Measurement Methods

2.3.1. Plant Growth and Basal Stem Growth

The plant growth (plant height) of young apple trees was measured with a steel tape measure, starting from the base rootstock to the highest point of the tree, once on the last day of each reproductive period, and the difference between the two measurements was the plant growth (cm) of that reproductive period. The growth (stem thickness) of the rootstock was measured with electronic vernier calipers using the crossover method, and the average value (mm) was taken.

2.3.2. Leaf Area

Individual leaf area was measured using a handheld leaf area meter (LI-3000C, LI-COR Technology Company, Lincoln, NE, USA) on the last day of each reproductive period, and 10 leaves from different orientations of the tree were randomly selected to take the average value for the determination.

The plant leaf area (m^2 $plant^{-1}$) was calculated as [29]:

$$\text{Plant leaf area} = \text{single leaf area} \times \text{total number of leaves} \tag{1}$$

2.3.3. Chlorophyll SPAD Value

A portable chlorophyll meter (SPAD-502, Konica-Minolta Company, Osaka, Japan) was used to determine the chlorophyll SPAD values, and the average value was taken from 10 randomly selected apple leaves per plant.

2.3.4. Photosynthetic Characteristics and Water Use Efficiency (WUE)

Photosynthetic characteristics of apples were determined using a photosynthesis meter (LI-6400, LI-COR Technology Company, Lincoln, NE, USA) and measured at 10:00 a.m. during the fruit-setting and expansion stage (10 June 2019 and 10 June 2020), when apple water needs are critical, and five healthy leaves were selected for each treatment to take the average. The measurement indexes included photosynthetic rate (Pn), transpiration rate (Tr), and stomatal conductance (Gs).

The leaf water use efficiency (WUE, μmol $mmol^{-1}$) was calculated as:

$$\text{WUE} = \text{Pn}/\text{Tr} \tag{2}$$

2.3.5. Dry Matter (DM), Water Consumption (ET), and Crop Water Productivity (CWP)

The plant samples (36 young apple trees with 12 treatments each year) were oven-dried at 75 °C until they reached a constant weight to determine the total dry matter content (DM).

Crop water consumption (ET) was calculated as [30]:

$$\text{ET} = \text{P} + \text{U} + \text{I} - \text{F} - \text{R} - \Delta\text{W} \tag{3}$$

where P is the precipitation; U is the groundwater recharge; I is the amount of irrigation; R is the runoff; F is the deep seepage; and ΔW is the change in soil moisture from the beginning to the end of the trial. According to the actual conditions during the experiments, the contributions of precipitation, groundwater recharge, runoff, and deep seepage were negligible.

Crop water productivity (CWP, $kg \cdot m^{-3}$) was calculated as below [31,32]:

$$\text{CWP} = \text{DM}/\text{ET} \tag{4}$$

where DM is the dry matter and ET is the water consumption.

2.4. Statistical Analysis

Microsoft Excel 2016 was used for statistical analysis; multiple comparisons of means were performed using the Duncan test at the 0.05 probability level ($p < 0.05$); and analysis of variance (ANOVA) and significance tests were performed using SPSS Statistics 19.0 statistical software. ANOVA was performed with water irrigation (W) and fertilizer application (F) as the main effects, and the interaction of the two factors was considered.

3. Results

3.1. Plant Growth

The plant growth of young apple trees in 2020 was greater than that in 2019 (Table 3). Irrigation had significant effects on the plant growth of young apple trees during the mature period in 2019 and 2020 ($p < 0.05$) and highly significant effects during other growing periods ($p < 0.01$). The plant growth of young apple trees increased first and then declined at each growth stage, reaching its maximum at the shoot growth stage. The plant growth increased first and then generally declined with the amount of irrigation under F1 and F2, and increased with the increase of irrigation under F3. The two-year average plant growth under W2 was 3.0%, 15.9%, and 34.7% at the budding and flowering stage, 0.4%, 9.0%, and 22.2% at the shoot growth stage, 5.0%, 13.0%, and 32.7% at the fruit-setting and expansion stage, 2.5%, 25.5%, and 38.7% at the mature period, and 2.6%, 14.1%, and 30.3% at the whole reproductive period, greater than that of W1, W3, and W4.

Table 3. Effect of different irrigation and fertilizer applications on plant growth of young apple trees at different reproductive stages in 2019 and 2020.

Year	Fertilization Level	Irrigation Level	Budding and Flowering Stage (cm)	Shoot Growth Stage (cm)	Fruit-Setting and Expansion Stage (cm)	Mature Period (cm)	Whole Reproductive Period (cm)
2019	F1	W1	10.2 ± 0.8 ab	14.5 ± 0.9 ab	11.8 ± 1.3 ab	7.4 ± 1.1 ab	43.8 ± 4.2 ab
		W2	10.9 ± 1.4 a	15.4 ± 1.0 a	13.1 ± 1.1 a	7.6 ± 1.1 a	47.0 ± 4.7 a
		W3	8.6 ± 1.60 abc	14.0 ± 0.5 abc	10.8 ± 1.6 abc	6.9 ± 0.8 ab	40.1 ± 4.5 abc
		W4	6.9 ± 0.8 cd	12.6 ± 0.3 bcd	9.1 ± 0.9 bcd	5.7 ± 0.4 abcd	34.2 ± 2.7 bcd
	F2	W1	8.4 ± 1.4 abc	14.0 ± 0.6 abc	10.4 ± 0.9 abc	6.7 ± 1.2 abc	39.4 ± 4.1 abc
		W2	8.8 ± 1.3 abc	15.0 ± 0.6 a	11.3 ± 1.9 abc	7.2 ± 1.7 ab	42.3 ± 5.4 ab
		W3	7.7 ± 1.7 bcd	13.4 ± 0.5 abcd	9.8 ± 0.9 bc	4.9 ± 1.1 bcd	35.7 ± 4.2 bc
		W4	7.1 ± 1.6 cd	12.0 ± 0.5 cde	8.9 ± 1.1 cd	4.3 ± 0.9 cd	32.1 ± 4.1 cd
	F3	W1	7.6 ± 1.0 bcd	14.0 ± 0.4 abc	9.8 ± 0.8 bc	5.8 ± 1.1 abcd	37.2 ± 3.3 abc
		W2	7.2 ± 0.9 bcd	12.3 ± 1.6 cd	9.4 ± 0.7 bc	5.6 ± 1.4 abcd	34.4 ± 4.7 bcd
		W3	6.7 ± 1.0 cd	11.5 ± 1.5 de	8.9 ± 0.4 cd	3.9 ± 0.4 d	30.9 ± 3.2 cd
		W4	5.1 ± 1.0 d	10.1 ± 1.0 e	6.4 ± 1.1 d	3.8 ± 0.5 d	25.4 ± 3.5 d
	Irrigation		**	**	**	*	**
	Fertilization		*	*	*	*	**
	Irrigation×Fertilization		**	*	ns	**	**
2020	F1	W1	12.4 ± 1.0 ab	17.1 ± 1.1 abc	14.8 ± 1.6 ab	9.3 ± 1.3 a	53.6 ± 5.1 ab
		W2	13.6 ± 1.1 a	18.1 ± 1.2 a	16.1 ± 1.4 a	9.6 ± 1.3 a	57.3 ± 4.9 a
		W3	10.8 ± 1.8 abcd	16.6 ± 0.7 abc	13.8 ± 1.9 ab	8.9 ± 0.9 ab	50.0 ± 5.4 abc
		W4	9.1 ± 1.0 cd	15.3 ± 0.5 abc	12.4 ± 1.1 bc	5.6 ± 0.6 abc	44.2 ± 3.2 bcd
	F2	W1	10.7 ± 1.6 abcd	16.7 ± 0.8 abc	13.4 ± 1.2 ab	8.7 ± 1.3 abc	49.3 ± 4.9 abc
		W2	11.2 ± 1.3 abc	17.6 ± 0.9 ab	14.2 ± 2.2 ab	9.2 ± 1.8 a	52.2 ± 6.2 abc
		W3	10.0 ± 1.9 bcd	16.0 ± 0.7 abc	12.7 ± 1.2 ab	7.0 ± 1.1 abc	45.7 ± 4.9 abcd
		W4	9.4 ± 1.8 bcd	14.6 ± 0.7 bcd	11.8 ± 1.3 bc	6.3 ± 1.1 bc	42.0 ± 4.9 bcd
	F3	W1	10.0 ± 1.0 bcd	16.6 ± 0.6 abc	12.9 ± 1.1 ab	7.8 ± 1.3 abc	47.3 ± 3.9 abc
		W2	9.4 ± 1.1 bcd	14.9 ± 1.8 bc	12.4 ± 1.0 bc	7.6 ± 1.6 abc	44.3 ± 5.5 bcd
		W3	9.0 ± 1.2 cd	14.1 ± 1.7 cd	11.8 ± 0.6 bc	5.9 ± 0.5 c	40.8 ± 4.0 cd
		W4	7.9 ± 0.5 d	11.8 ± 2.6 d	9.2 ± 1.6 c	6.1 ± 0.4 bc	34.9 ± 5.0 d
	Irrigation		**	**	**	*	**
	Fertilization		*	ns	*	*	**
	Irrigation×Fertilization		**	ns	ns	**	*

Notes: W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O). ns indicates not significant, * indicates significant difference ($p < 0.05$), ** indicates highly significant difference ($p < 0.01$); different letters after the same column of numbers indicate differences at the $p < 0.05$ significant level.

Fertilization had significant effects on plant growth during each growing period in 2019 ($p < 0.05$), no significant effects on plant growth at the shoot growth stage in 2020, and significant effects during other growing periods in 2020 ($p < 0.05$). Under the same irrigation amount, the growth of young apple plants increased with the increase in fertilizer, following the order of F1 > F2 > F3. The two-year average plant growth under F1 was 12.6% and 31.2% at the budding and flowering stage, by 3.6% and 17.4% at the shoot growth stage, by 10.0% and 25.9% at the fruit-setting and expansion stage, by 16.5% and 35.8% at the mature period, and by 9.3% and 25.5% at the whole reproductive period, greater than that under F2 and F3.

Irrigation × fertilization had highly significant effects on plant growth at the budding and flowering stage and mature period in 2019 and 2020 ($p < 0.01$), and significant effects at the shoot growth stage in 2019 ($p < 0.05$). At the shoot growth stage, the plant growth reached the maximum value under F1W2 of 15.4 cm in 2019 and 18.1 cm in 2020, which increased by 2.7–52.5% in 2019 and 2.8–53.4% in 2020 compared with other treatments, respectively.

3.2. Basal Stem Growth

The basal stem growth of young apple trees in 2020 was greater than that in 2019 (Table 4). Irrigation had highly significant effects on basal stem growth at each growing period in 2019 and 2020 ($p < 0.01$), which increased with the amount of irrigation, following the order of W1≈W2 > W3 > W4. The two-year average basal stem growth under W2 was 23.1% and 76.5% at the budding and flowering stage, by 29.0% and 75.8% at the shoot growth stage, by 20.7% and 60.9% at the fruit-setting and expansion stage, by 23.9% and 52.5% at the mature period, and by 24.0% and 64.6% at the whole reproductive period, greater than that under W3 and W4.

Table 4. Effect of different irrigation and fertilizer applications on basal stem growth of young apple trees at different reproductive stages in 2019 and 2020.

Year	Fertilization Level	Irrigation Level	Budding and Flowering Stage (mm)	Shoot Growth Stage (mm)	Fruit-Setting and Expansion Stage (mm)	Mature Period (mm)	Whole Reproductive Period (mm)
2019	F1	W1	1.76 ± 0.16 ab	1.99 ± 0.17 a	2.33 ± 0.11 ab	2.48 ± 0.16 a	8.55 ± 0.61 ab
		W2	1.82 ± 0.18 a	2.10 ± 0.16 a	2.46 ± 0.18 a	2.52 ± 0.15 a	8.90 ± 0.67 a
		W3	1.49 ± 0.25 abcd	1.70 ± 0.12 abc	1.88 ± 0.04 de	2.03 ± 0.08 cd	7.10 ± 0.50 bcd
		W4	1.11 ± 0.18 cd	1.27 ± 0.18 d	1.50 ± 0.17 f	1.65 ± 0.09 e	5.52 ± 0.62 ef
	F2	W1	1.68 ± 0.21 ab	1.95 ± 0.08 ab	2.25 ± 0.11 abc	2.35 ± 0.14 ab	8.23 ± 0.54 abc
		W2	1.71 ± 0.28 ab	1.98 ± 0.23 ab	2.30 ± 0.16 ab	2.41 ± 0.11 ab	8.39 ± 0.78 ab
		W3	1.38 ± 0.28 abcd	1.55 ± 0.20 bcd	1.92 ± 0.10 cde	1.97 ± 0.12 cd	6.82 ± 0.69 cde
		W4	0.98 ± 0.21 de	1.19 ± 0.14 d	1.40 ± 0.16 fg	1.62 ± 0.04 e	5.19 ± 0.47 f
	F3	W1	1.59 ± 0.20 abc	1.90 ± 0.13 ab	2.06 ± 0.15 bcd	2.23 ± 0.08 abc	7.78 ± 0.56 abc
		W2	1.64 ± 0.21 ab	1.89 ± 0.13 ab	2.11 ± 0.17 bcd	2.14 ± 0.18 bc	7.77 ± 0.69 abc
		W3	1.25 ± 0.19 bcd	1.36 ± 0.18 cd	1.72 ± 0.09 ef	1.76 ± 0.19 ef	6.08 ± 0.64 def
		W4	0.59 ± 0.22 e	0.72 ± 0.30 e	1.13 ± 0.22 g	1.32 ± 0.09 f	3.75 ± 0.83 g
	Irrigation		**	**	**	**	**
	Fertilization		*	**	**	*	**
	Irrigation × Fertilization		**	*	**	ns	**
2020	F1	W1	2.01 ± 0.16 a	2.18 ± 0.18 ab	2.74 ± 0.16 a	2.62 ± 0.19 a	9.54 ± 0.70 a
		W2	1.93 ± 0.12 ab	2.28 ± 0.16 a	2.63 ± 0.13 ab	2.72 ± 0.18 a	9.55 ± 0.59 a
		W3	1.66 ± 0.13 bc	1.83 ± 0.05 bcd	2.16 ± 0.08 cd	2.15 ± 0.09 cde	7.79 ± 0.35 bcd
		W4	1.26 ± 0.10 de	1.46 ± 0.19 e	1.78 ± 0.16 e	1.81 ± 0.03 fg	6.31 ± 0.47 ef
	F2	W1	1.90 ± 0.13 ab	2.14 ± 0.10 ab	2.59 ± 0.18 ab	2.47 ± 0.15 abc	9.10 ± 0.54 ab
		W2	1.84 ± 0.11 abc	2.17 ± 0.11 ab	2.52 ± 0.14 abc	2.57 ± 0.16 ab	9.10 ± 0.52 ab
		W3	1.53 ± 0.14 cd	1.68 ± 0.13 cde	2.21 ± 0.11 cd	2.06 ± 0.07 def	7.48 ± 0.45 cde
		W4	1.15 ± 0.09 ef	1.36 ± 0.13 ef	1.70 ± 0.16 ef	1.71 ± 0.05 gh	5.91 ± 0.43 fg
	F3	W1	1.75 ± 0.08 abc	1.93 ± 0.06 abc	2.38 ± 0.20 abc	2.27 ± 0.11 bcd	8.33 ± 0.45 abc
		W2	1.69 ± 0.06 bc	1.97 ± 0.13 abc	2.33 ± 0.17 bcd	2.26 ± 0.18 bcd	8.24 ± 0.55 abc
		W3	1.32 ± 0.16 de	1.49 ± 0.25 de	2.01 ± 0.10 de	1.84 ± 0.12 efg	6.65 ± 0.62 def
		W4	0.94 ± 0.22 f	1.05 ± 0.23 f	1.42 ± 0.21 f	1.49 ± 0.23 h	4.89 ± 0.90 g
	Irrigation		**	**	**	**	**
	Fertilization		**	*	**	*	**
	Irrigation × Fertilization		ns	ns	**	ns	ns

Notes: W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O). ns indicates not significant, * indicates significant difference ($p < 0.05$), ** indicates highly significant difference ($p < 0.01$); different letters after the same column of numbers indicate differences at the $p < 0.05$ significant level.

Fertilization had highly significant effects on basal stem growth at the fruit-setting and expansion stage and whole growing period in 2019 and 2020 ($p < 0.01$), and significant effects at the mature period in 2019 and 2020 ($p < 0.05$). Under the same irrigation amount, the basal stem growth of young apple trees increased with the increase in fertilizer amount, following the order of F1 > F2 > F3. The average two-year basal stem growth under F1 was 7.0% and 21.1% at the budding and flowering stage, by 5.6% and 20.2% at the shoot growth stage, by 3.5% and 15.4% at the fruit-setting and expansion stage, by 4.7% and 17.5% at the mature period, and by 5.0% and 18.3% at the whole reproductive period, greater than that under F2 and F3.

Irrigation × fertilization had highly significant effects on basal stem growth at the budding and flowering stage, fruit-setting and expansion stage, and whole growing period in 2019 ($p < 0.01$), and significant effects at the shoot growth stage in 2019 ($p < 0.05$), and highly significant effects at the fruit-setting and expansion stage in 2020 ($p < 0.01$), and no significant effects during other growing periods in 2020. At the mature period, the basal stem growth of young apple trees reached the maximum value under F1W2 of 2.52 mm in 2019 and 2.72 mm in 2020, which increased by 1.6–90.9% in 2019 and 3.8–82.6% in 2020 compared with other treatments, respectively.

3.3. Leaf Area

The leaf area of young apple trees in 2020 was greater than that in 2019 (Table 5). Irrigation had highly significant effects on the leaf area of young apples at each growing period in 2019 and 2020 ($p < 0.01$). The leaf area of young apple trees in 2019 increased first and then generally declined with irrigation water at each growing period under F1 and F2, and increased with the increase of irrigation under F3. The leaf area at the budding and flowering stages followed the order of W1 > W2 > W3 > W4 under the same fertilizer amount in 2020, and the leaf areas at the shoot growth stage, fruit-setting and expansion stage, and mature period followed the order of W2 > W1 > W3 > W4. The two-year average leaf area under W2 was 1.1%, 21.3%, and 40.4% at the budding and flowering stage; 3.1%, 20.7%, and 42.2% at the shoot growth stage; 2.6%, 21.4%, and 38.6% at the fruit-setting and expansion stage; and 3.1%, 20.4%, and 35.7% at the mature period, which was greater than that under W1, W3, and W4.

Fertilization had significant effects on leaf area at the budding and flowering stage and fruit-setting and expansion stage in 2019 and 2020 ($p < 0.05$), highly significant effects on the shoot growth stage in 2019 ($p < 0.01$), and no significant effects at the mature period in 2019. Under the same irrigation amount, the leaf area of young apple trees increased with the increase in fertilizer, following the order of F1 > F2 > F3. The average two-year leaf area under F1 was 7.7% and 22.5% at the budding and flowering stage, 11.4% and 22.8% at the shoot growth stage, 9.5% and 19.4% at the fruit-setting and expansion stage, and 9.2% and 19.8% at the mature period, greater than that under F2 and F3.

In 2019, irrigation × fertilization had highly significant effects on leaf area at the budding and flowering stage and fruit-setting and expansion stage ($p < 0.01$) and no significant effects during other growing periods. In 2020, irrigation × fertilization had significant effects on leaf area at the shoot growth stage and fruit-setting and expansion stage ($p < 0.05$), highly significant effects at the mature period ($p < 0.01$), and no significant effects at the budding and flowering stage. At the mature period, the leaf area of young apple trees reached the maximum value under F1W2 of 2.19 m^2 $plant^{-1}$ in 2019 and 2.58 m^2 $plant^{-1}$ in 2020, which increased by 3.3–64.7% in 2019 and 7.1–60.2% in 2020 compared with other treatments, respectively.

Table 5. Effect of different irrigation and fertilizer applications on the leaf area of young apple trees at different reproductive stages in 2019 and 2020.

Year	Fertilization Level	Irrigation Level	Budding and Flowering Stage (m^2 $plants^{-1}$)	Shoot Growth Stage (m^2 $plants^{-1}$)	Fruit-Setting and Expansion Stage (m^2 $plants^{-1}$)	Mature Period (m^2 $plants^{-1}$)
2019	F1	W1	1.18 ± 0.09 ^{abc}	1.71 ± 0.14 ^{a}	2.01 ± 0.22 ^{ab}	2.12 ± 0.16 ^{a}
		W2	1.29 ± 0.14 ^{a}	1.81 ± 0.15 ^{a}	2.11 ± 0.16 ^{a}	2.19 ± 0.25 ^{a}
		W3	1.00 ± 0.13 ^{bcde}	1.52 ± 0.15 ^{abc}	1.68 ± 0.13 ^{bcde}	1.74 ± 0.12 ^{bc}
		W4	0.87 ± 0.13 ^{def}	1.31 ± 0.17 ^{bcde}	1.47 ± 0.19 ^{defg}	1.61 ± 0.14 ^{bcd}
	F2	W1	1.11 ± 0.11 ^{abcd}	1.53 ± 0.16 ^{ab}	1.80 ± 0.13 ^{abcd}	1.94 ± 0.22 ^{ab}
		W2	1.19 ± 0.11 ^{ab}	1.60 ± 0.12 ^{ab}	1.87 ± 0.10 ^{abc}	1.96 ± 0.18 ^{ab}
		W3	0.93 ± 0.11 ^{def}	1.34 ± 0.09 ^{bcde}	1.58 ± 0.16 ^{cdefg}	1.71 ± 0.01 ^{bc}
		W4	0.80 ± 0.12 ^{ef}	1.16 ± 0.20 ^{de}	1.32 ± 0.16 ^{fg}	1.35 ± 0.17 ^{d}
	F3	W1	1.00 ± 0.07 ^{bcde}	1.51 ± 0.11 ^{abcd}	1.70 ± 0.11 ^{bcde}	1.86 ± 0.10 ^{ab}
		W2	0.94 ± 0.08 ^{cdef}	1.35 ± 0.08 ^{bcde}	1.61 ± 0.11 ^{cdef}	1.71 ± 0.01 ^{bc}
		W3	0.88 ± 0.01 ^{def}	1.17 ± 0.21 ^{cde}	1.40 ± 0.11 ^{efg}	1.49 ± 0.10 ^{cd}
		W4	0.70 ± 0.08 ^{f}	1.03 ± 0.13 ^{e}	1.23 ± 0.12 ^{g}	1.33 ± 0.05 ^{d}
	Irrigation		**	**	**	**
	Fertilization		*	**	*	ns
	Irrigation × Fertilization		**	ns	**	ns
2020	F1	W1	1.44 ± 0.16 ^{a}	1.92 ± 0.10 ^{ab}	2.27 ± 0.16 ^{ab}	2.41 ± 0.15 ^{ab}
		W2	1.35 ± 0.11 ^{ab}	2.05 ± 0.19 ^{a}	2.38 ± 0.13 ^{a}	2.58 ± 0.13 ^{a}
		W3	1.15 ± 0.10 ^{abcde}	1.67 ± 0.06 ^{bcd}	1.87 ± 0.06 ^{cdef}	2.07 ± 0.11 ^{cd}
		W4	0.99 ± 0.13 ^{def}	1.28 ± 0.06 ^{fg}	1.66 ± 0.12 ^{efg}	1.85 ± 0.09 ^{def}
	F2	W1	1.31 ± 0.14 ^{abc}	1.72 ± 0.13 ^{bcd}	2.06 ± 0.18 ^{abcd}	2.20 ± 0.11 ^{bc}
		W2	1.29 ± 0.12 ^{abc}	1.83 ± 0.18 ^{abc}	2.17 ± 0.15 ^{abc}	2.35 ± 0.12 ^{ab}
		W3	1.05 ± 0.17 ^{cdef}	1.49 ± 0.09 ^{def}	1.76 ± 0.08 ^{defg}	1.92 ± 0.10 ^{de}
		W4	0.92 ± 0.10 ^{ef}	1.24 ± 0.06 ^{fg}	1.56 ± 0.17 ^{fg}	1.76 ± 0.05 ^{ef}
	F3	W1	1.21 ± 0.07 ^{abcd}	1.57 ± 0.08 ^{cde}	1.94 ± 0.12 ^{bcde}	1.97 ± 0.08 ^{cde}
		W2	1.11 ± 0.01 ^{bcde}	1.63 ± 0.08 ^{cd}	1.94 ± 0.25 ^{bcde}	2.09 ± 0.08 ^{cd}
		W3	0.90 ± 0.13 ^{ef}	1.32 ± 0.10 ^{efg}	1.66 ± 0.11 ^{efg}	1.78 ± 0.11 ^{ef}
		W4	0.82 ± 0.11 ^{f}	1.22 ± 0.12 ^{g}	1.47 ± 0.13 ^{g}	1.61 ± 0.09 ^{f}
	Irrigation		**	**	**	**
	Fertilization		*	**	**	**
	Irrigation × Fertilization		ns	*	*	**

Notes: W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O). ns indicates not significant, * indicates significant difference ($p < 0.05$), ** indicates highly significant difference ($p < 0.01$); different letters after the same column of numbers indicate differences at the $p < 0.05$ significant level.

3.4. SPAD

The SPAD of young apple trees in 2020 was greater than that in 2019 (Figure 3). Irrigation had significant effects on SPAD at the shoot growth stage ($p < 0.05$) and highly significant effects at the fruit-setting and expansion stage and mature period ($p < 0.01$). As young apple trees grew and developed, SPAD increased significantly in the middle and early stages of growth, with the increase leveling off gradually after maturity. The SPAD of young apple trees in 2019 followed the order of W2 > W1 > W3 > W4 at the shoot growth stage under F1 and F2 and followed the order of W1 > W2 > W3 > W4 at each growing period under F3. Under the same fertilizer amount in 2020, the SPAD at the budding and flowering stage and shoot growth stage followed the order of W2 > W1 > W3 > W4, and at the fruit-setting and expansion stage and mature period followed the order of W1 > W2 > W3 > W4. Fertilization had significant effects on SPAD at the shoot growth stage ($p < 0.05$) and highly significant effects at the mature period ($p < 0.01$). Under the same irrigation amount, the SPAD of young apple trees increased with the increase in fertilizer, following the order of F1 > F2 > F3.

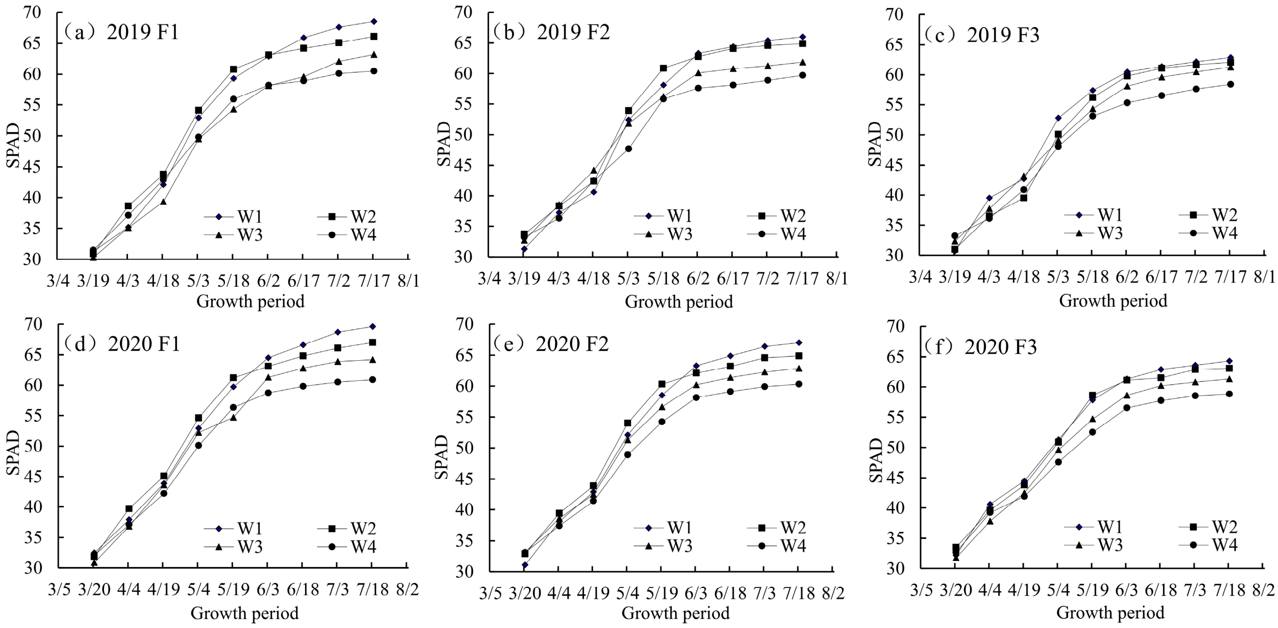

Figure 3. Effect of different irrigation and fertilizer applications on the chlorophyll content (SPAD) of young apple trees at different periods in 2019 and 2020 (**a**–**c**): effects of three fertilization levels on SPAD of young apple trees in 2019; (**d**–**f**): effects of three fertilization levels on SPAD of young apple trees in 2020 W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O).

Irrigation × fertilization had highly significant effects on SPAD at the mature period ($p < 0.01$). In 2019, the SPAD of young apple trees reached the maximum value of 57.5 under F1W2 at the shoot growth stage and reached the maximum value of 64.4 and 68.1 under F1W1 at fruit-setting and expansion stage and mature period, respectively; all reached the minimum value of 50.6, 55.9, and 58.0 under F3W4, and the maximum value increased by 13.6%, 15.2%, and 17.4% over the minimum value, respectively. In 2020, the SPAD of young apple trees reached the maximum value of 57.9 under F1W2 at the shoot growth stage and reached the maximum values of 65.6 and 69.2 under F1W1 at fruit-setting and expansion stage and mature period, respectively; all reached the minimum values of 50.1, 57.1, and 58.7 under F3W4, and the maximum values increased by 15.6%, 14.9%, and 17.9% than the minimum values, respectively.

3.5. Dry Matter (DM), Water Consumption (ET) and Crop Water Productivity (CWP)

The dry matter (DM) of young apple trees in 2020 was greater than that in 2019 (Table 6). Irrigation had highly significant effects on dry matter in 2019 and 2020 ($p < 0.01$). The dry matter increased first and then generally declined with irrigation under F1 and F2, and the two-year average dry matter under W2 was 0.4%, 10.5%, and 26.3% greater than that under W1, W3, and W4, respectively. The dry matter increased with the increase in irrigation under F3, following the order of W1 > W2 > W3 > W4. Fertilization had significant effects on dry matter in 2019 ($p < 0.05$) and highly significant effects in 2020 ($p < 0.01$). Under the same amount of irrigation, the dry matter of young apple trees increased with the increase of fertilizer, following the order of F1 > F2 > F3, and the two-year average dry matter under F1 was 6.3% and 13.2% greater than that under F2 and F3, respectively. Irrigation × fertilization had significant effects on the dry matter in 2019 and 2020 ($p < 0.05$). F1W2 in 2019 and 2020 obtained the maximum dry matter of 543.3 g plant^{-1} and 654.1 g plant^{-1}, which increased by 0.8–42.8% in 2019 and 0.6–40.0% in 2020 compared with other treatments, respectively.

Table 6. Effect of different irrigation and fertilizer applications on dry matter (DM), water consumption (ET), and water productivity (WP) of young apple trees throughout the reproductive period in 2019 and 2020.

Year	Fertilization Level	Irrigation Level	Dry Matter (g plants^{-1})	Water Consumption (L plants^{-1})	Water Productivity (kg m^{-3})
2019	F1	W1	539.05 ± 18.77 ^{ab}	255.21 ± 11.31 ^{a}	2.12 ± 0.02 ^{d}
		W2	543.27 ± 26.87 ^{a}	224.03 ± 9.19 ^{bcd}	2.43 ± 0.02 ^{a}
		W3	482.88 ± 31.90 ^{bcd}	203.15 ± 13.86 ^{de}	2.38 ± 0.01 ^{ab}
		W4	416.13 ± 21.92 ^{ef}	178.91 ± 11.00 ^{fgh}	2.33 ± 0.02 ^{ab}
	F2	W1	508.71 ± 23.33 ^{abc}	241.02 ± 9.90 ^{ab}	2.11 ± 0.01 ^{d}
		W2	509.20 ± 14.81 ^{abc}	215.15 ± 8.49 ^{cd}	2.37 ± 0.02 ^{ab}
		W3	459.47 ± 24.96 ^{cde}	192.40 ± 9.21 ^{ef}	2.39 ± 0.01 ^{ab}
		W4	394.98 ± 36.70 ^{f}	170.42 ± 10.61 ^{gh}	2.32 ± 0.07 ^{b}
	F3	W1	504.68 ± 8.49 ^{abc}	233.76 ± 6.65 ^{bc}	2.16 ± 0.03 ^{cd}
		W2	459.52 ± 20.66 ^{cde}	206.63 ± 3.54 ^{de}	2.23 ± 0.06 ^{c}
		W3	434.82 ± 29.13 ^{def}	185.31 ± 5.55 ^{efg}	2.35 ± 0.09 ^{ab}
		W4	380.51 ± 14.48 ^{f}	163.44 ± 7.07 ^{h}	2.33 ± 0.01 ^{ab}
	Irrigation		**	**	**
	Fertilization		*	*	ns
	Irrigation×Fertilization		*	ns	ns
2020	F1	W1	649.84 ± 22.31 ^{ab}	299.19 ± 8.92 ^{a}	2.17 ± 0.01 ^{c}
		W2	654.06 ± 30.41 ^{a}	271.01 ± 11.04 ^{bcd}	2.41 ± 0.01 ^{a}
		W3	593.67 ± 35.43 ^{abcd}	251.63 ± 17.83 ^{cdef}	2.36 ± 0.03 ^{ab}
		W4	526.92 ± 25.46 ^{efg}	227.39 ± 14.97 ^{fghi}	2.32 ± 0.04 ^{ab}
	F2	W1	609.18 ± 26.03 ^{abc}	284.32 ± 11.55 ^{ab}	2.15 ± 0.01 ^{c}
		W2	609.66 ± 17.51 ^{abc}	258.95 ± 10.84 ^{bcde}	2.36 ± 0.04 ^{ab}
		W3	559.94 ± 27.65 ^{cdef}	234.20 ± 8.73 ^{efgh}	2.39 ± 0.03 ^{ab}
		W4	495.45 ± 39.39 ^{fg}	214.22 ± 12.96 ^{hi}	2.31 ± 0.04 ^{b}
	F3	W1	586.38 ± 15.60 ^{bcde}	274.93 ± 5.94 ^{abc}	2.14 ± 0.01 ^{c}
		W2	541.22 ± 27.78 ^{def}	245.80 ± 5.66 ^{defg}	2.21 ± 0.06 ^{c}
		W3	516.52 ± 36.25 ^{fg}	224.48 ± 7.67 ^{ghi}	2.30 ± 0.08 ^{b}
		W4	467.21 ± 14.52 ^{g}	202.61 ± 9.19 ^{i}	2.31 ± 0.04 ^{b}
	Irrigation		**	**	**
	Fertilization		**	*	ns
	Irrigation ×Fertilization		*	ns	ns

Notes: W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O). ns indicates not significant, * indicates significant difference ($p < 0.05$), ** indicates highly significant difference ($p < 0.01$); different letters after the same column of numbers indicate differences at the $p < 0.05$ significant level.

The water consumption of young apple trees in 2020 was greater than that in 2019 (Table 6). Irrigation had highly significant effects on water consumption and water productivity in 2019 and 2020 ($p < 0.01$). Fertilization had no significant effects on water productivity in 2019 and 2020. The water consumption of young apple trees at each growing period in both years increased with the increase of irrigation, under the same irrigation amount, following the order of F1 > F2 > F3, and under the same fertilizer amount, following the order of W1 > W2 > W3 > W4. During the whole reproductive period, the water productivity of young apple trees followed the order of W2 > W3 > W4 > W1 under F1, W3 > W2 > W4 > W1 under F2, W3 > W4 > W2 > W1 in 2019, and W4 > W3 > W2 > W1 in 2020 under F3. F1W2 in 2019 and 2020 obtained the maximum water productivity of 2.43 kg m^{-3} and 2.41 kg m^{-3}, which increased by 1.7–15.2% in 2019 and 0.8–12.6% in 2020 compared with other treatments, respectively.

Both dry matter and water productivity of young apple trees reached their maximum under F1W2, which increased by 0.8%, or 14.6%, in 2019 and 0.6%, or 11.1%, in 2020 compared with F1W1, while water consumption decreased by 12.2% and 9.4% in both years.

3.6. Photosynthetic Characteristics and Water Use Efficiency (WUE)

The photosynthetic rate (Pn), transpiration rate (Tr), and stomatal conductance (Gs) of young apple trees in 2020 were greater than those in 2019 (Figure 4). Irrigation had highly significant effects on Pn, Tr, and Gs in 2019 and 2020 ($p < 0.01$). Under the same fertilizer amount, Pn, Tr, and Gs of young apple trees increased with the increase in irrigation, following the order of W1 > W2 > W3 > W4. The two-year average Pn and Tr under W1 were 4.8%, 19.9%, 36.0%, and 10.0%, 17.0%, and 26.7% greater than those under W2, W3, and W4, respectively. Fertilization had significant effects on Pn in 2019 and 2020 ($p < 0.05$), highly significant effects on Gs in 2019 ($p < 0.01$), and significant effects on Gs in 2020 ($p < 0.05$). Under the same irrigation amount, the Pn, Tr, and Gs of young apple trees increased with the increase of fertilizer, following the order of F1 > F2 > F3. The two-year average Pn and Tr under F1 were 5.0%, 15.2%, and 3.5%, respectively, 6.0% greater than those under F2 and F3, respectively. The Pn, Tr, and Gs of young apple trees in 2019 and 2020 reached their maximum under F1W1.

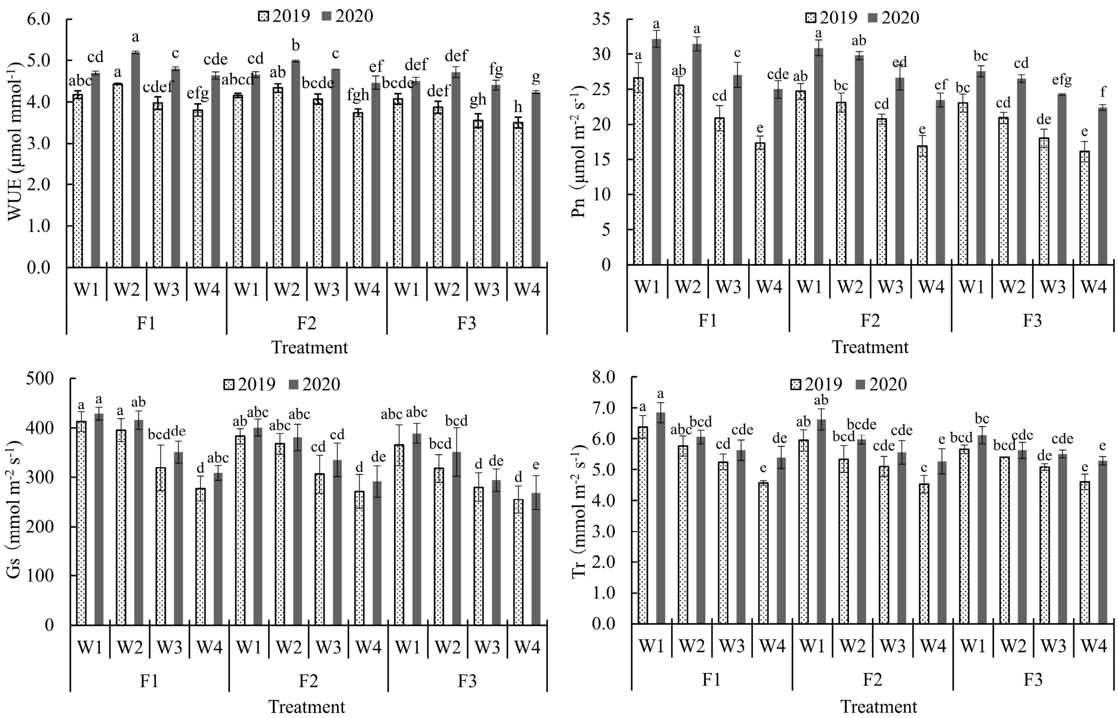

Figure 4. Effects of different irrigation and fertilizer applications on photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), and water use efficiency (WUE) of young apple trees in 2019 and 2020 W1 = sufficient irrigation (75–90% Fs); W2 = mild deficit (65–80% Fs); W3 = moderate deficit (55–70% Fs); W4 = severe deficit (45–60% Fs); Fs is the field water holding capacity. F1 = high level (27-9-9 g N-P_2O_5-K_2O); F2 = medium level (18-9-9 g N-P_2O_5-K_2O); F3 = low level (9-9-9 g N-P_2O_5-K_2O). Bars are the means ± standard deviation (n = 3). Different letters indicate the significance at the same growth stage between different treatments at the 5% level of the LSD test.

The water use efficiency (WUE) of young apple trees in 2020 was greater than that in 2019 (Figure 4). Irrigation had highly significant effects ($p < 0.01$) on WUE in 2019 and significant effects on WUE in 2020 ($p < 0.05$). Under the same fertilizer amount, WUE in 2019 followed the order of W2 > W1 > W3 > W4 under F1 and F2, and W1 > W2 > W3 > W4 under F3. The WUE in 2020 followed the order of W2 > W3 > W1 > W4 under F1 and F2, and

W2 > W1 > W3 > W4 under F3. The two-year average water use efficiency under W2 was 4.8%, 7.6%, and 12.9% greater than that under W1, W3, and W4, respectively. Fertilization had significant effects on WUE in 2019 and 2020 ($p < 0.05$). Under the same irrigation amount, the water use efficiency of young apple trees increased with the increase in fertilizer, following the order of F1 > F2 > F3. The two-year average water use efficiency under F1 was 1.5% and 8.7% greater than that under F2 and F3, respectively. Irrigation × fertilization had no significant effects on WUE in 2019 ($p < 0.01$) and significant effects on WUE in 2020 ($p < 0.05$). F1W2 in 2019 and in 2020 obtained the maximum WUE of 4.4 μmol mmol^{-1} in 2019 and 5.2 μmol mmol^{-1} in 2020, which increased by 2.3–25.7% in 2019 and 4.0–23.8% in 2020 compared with other treatments, respectively.

3.7. Correlations between Plant Growth and Other Physiological Indicators

Figure 5 shows the correlations between plant growth and net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE). It can be seen from the figure that there were good linear relationships between the growth of young apple plants and Pn, Tr, Gs, ET, and WUE with R^2 values of 0.7389, 0.5772, 0.8058, 0.6183, and 0.6665, respectively, which indicated that the growth of young apple plants was closely related to these indicators. The relationship between plant growth and WP of young apple trees was not significant, with an R^2 of only 0.001.

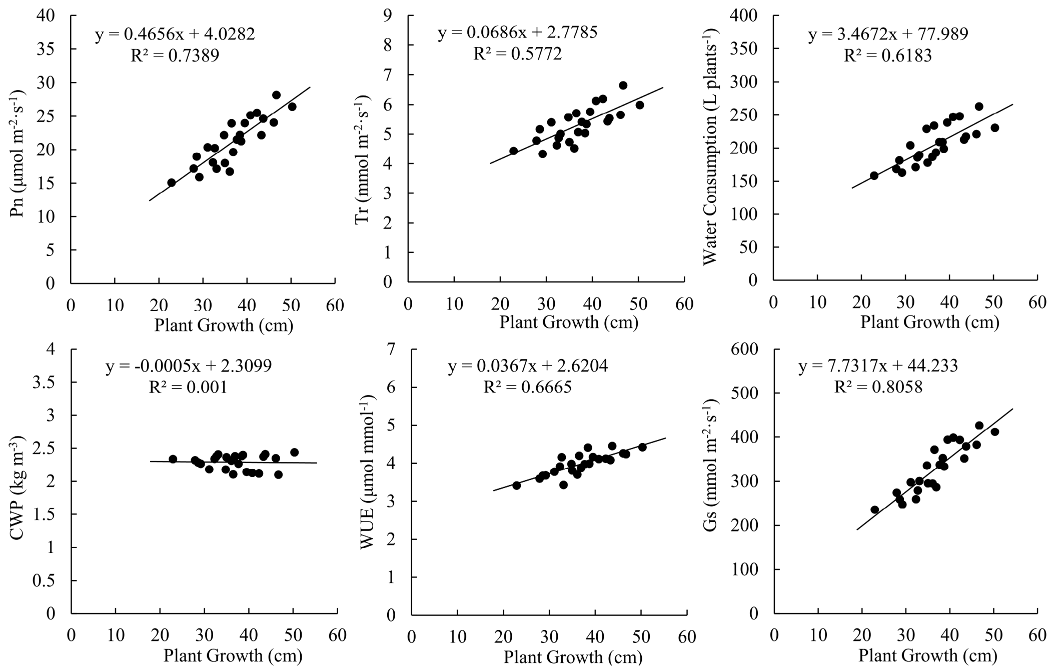

Figure 5. Relationships between plant growth and net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE) of young apple trees under different irrigation and fertilizer application treatments.

3.8. Correlation between Leaf Area and Other Physiological Indicators

Figure 6 shows the correlations between leaf area and net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE). It can be seen from the figure that there is a good linear relationship between leaf area of young apple trees and Pn, Tr, G, ET, and WUE with R^2 values of 0.867, 0.743, 0.8668, 0.7902, and 0.6774, respectively, which indicates that the growth of leaf area of young apple trees was closely related to these indicators. The relationship between leaf area and WP in young apple trees was not significant, with an R^2 of only 0.0464.

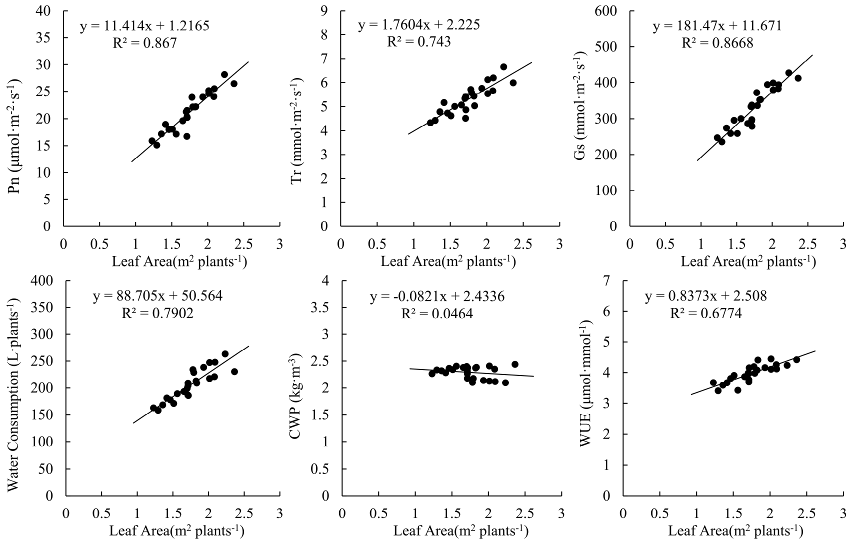

Figure 6. Relationships between leaf area and net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE) of young apple trees under different irrigation and fertilizer application treatments.

3.9. Correlation between Dry Matter (DM) and Other Indicators

Figure 7 shows the correlations between dry matter and plant growth, leaf area, chlorophyll (SPAD), net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE). It can be seen from the figure that there is a good linear relationship between the dry matter of young apple trees and plant growth, leaf area, SPAD, Pn, Tr, G, ET, WP, and WUE, with R^2 values of 0.8453, 0.9197, 0.8649, 0.8967, 0.801, 0.9245, 0.8628, and 0.6701, respectively, which indicates that the dry matter of young apple trees is closely related to these indicators. The R^2 between dry matter and water productivity of young apple trees was only 0.0523.

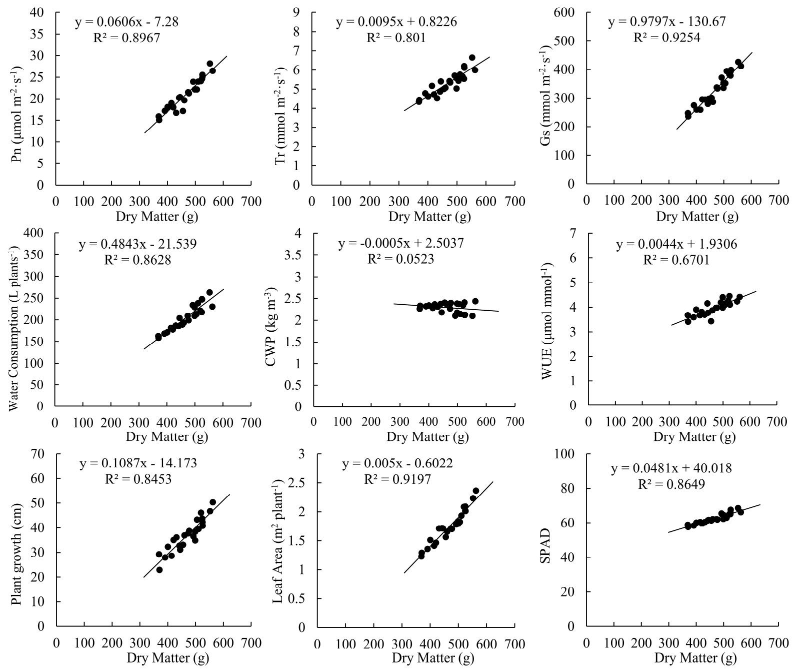

Figure 7. Relationships between dry matter mass (DM) and plant growth, leaf area, chlorophyll (SPAD), net photosynthetic rate (Pn), transpiration rate (Tr), stomatal conductance (Gs), water consumption (ET), water productivity (WP), and water use efficiency (WUE) of young apple trees under different treatments of irrigation and fertilizer application.

4. Discussion

4.1. Effect of Water-Fertilizer Coupling on the Growth and Dry Matter (DM) of Young Apple Trees

Water and fertilizer are critical factors affecting apple growth and development [21]. A reasonable amount of irrigation and fertilizer can effectively promote healthy crop growth [23,33]. Our study showed that mild deficit irrigation under high fertilizer conditions was beneficial in increasing plant growth, basal stem growth, leaf area, SPAD, and dry matter of young apple trees and increased with the increase of irrigation under low fertilizer. Previous studies have shown that cucumber yield under mild deficit irrigation and sufficient irrigation did not differ much under the same level of fertilization, while mild deficit irrigation was more water-efficient [34]. In addition, mild deficit irrigation under drip irrigation increased maize plant growth and yield [9], which is consistent with the conclusions reached in this study, which may be due to the fact that mild deficit irrigation moderately improves crop adaptability and stress tolerance and promotes root growth, which is beneficial to crop growth. However, deficit irrigation reduced LAI, tuber dry matter, and tuber fresh yield of potato compared to adequate irrigation [11], which is inconsistent with the conclusions reached in this study, considering the sensitivity of the different crops to water and the different experimental conditions, such as the climatic environment of the plantation. In the future, we will conduct in-depth research on the growth of different crops under water-fertilizer coupling.

In addition, irrigation, the application of nitrogen fertilizer can have beneficial effects on the growth and development of apples [35]. Our study showed that a reasonable increase in fertilizer application under the same irrigation conditions could increase plant growth, basal stem growth, leaf area, SPAD, and dry matter of young apple trees. Previous studies have shown that under suitable irrigation conditions, increased N fertilization can promote cotton growth and contribute to increased LAI, dry matter accumulation, crop growth rate, and relative growth rate [36,37], which is in agreement with the conclusions reached in this study, and this is due to the fact that high fertilizer application can to some extent compensate for the effect of reduced irrigation on plant growth [38].

There is a positive linear relationship between apple young tree yield and dry matter, and the apple young tree dry matter can reflect apple yield [29,39,40]. In this study, we have established the relationship between the dry matter of young apple trees and plant growth, leaf area, and SPAD, and the final product dry matter of young apple trees has a relatively good linear relationship with plant growth, leaf area, and SPAD (Figure 7). This indicates that the dry matter of young apple trees is closely related to these indicators, suggesting that the better the plant growth under mild deficit irrigation conditions, the more dry matter it will eventually accumulate, thus reflecting the greater yield of apples.

4.2. Effect of Water-Fertilizer Coupling on Water Consumption (ET) and Water Productivity (WP) of Young Apple Trees

Crop water productivity (CWP) reflects the input-output efficiency of water quantity [8] and also reflects the output of the crop in relation to water consumption. In our study, we found that young apple trees could not obtain high water productivity with sufficient water supply, and mild deficit irrigation was beneficial to improve the water productivity of young apple trees. The previous studies showed that water consumption increased with the increase of irrigation water during the whole reproductive period of the crop under different water and fertilizer conditions, and the water consumption gradually leveled off with the increase of irrigation water in the late reproductive period [29,41,42]. This result is consistent with the results of our study, where water consumption of young apple trees increased with the increase in irrigation and fertilizer. Liu et al. [43] showed that an appropriate increase in irrigation and nitrogen application could improve water productivity by studying the effects of different irrigation water and nitrogen fertilizer amounts on golden pear. Wang et al. [11] found that reasonable irrigation and fertilizer management can promote water and nutrient uptake in potatoes, and an appropriate reduction of irrigation water can improve water productivity in potatoes. Li et al. [44]

found that moderate deficit irrigation significantly improved tomato fruit quality and water productivity (WP). Under the same N application, WP decreased significantly with increasing irrigation [33]. Our study is in agreement with the results of previous studies, which may be due to the fact that irrigation water exceeded the irrigation water threshold and the overflow irrigation water could not be absorbed and used to form yield, resulting in lower crop water productivity.

4.3. Effect of Water-Fertilizer Coupling on Photosynthetic Characteristics and Water Use Efficiency (WUE) of Young Apple Trees

Photosynthetic rate (Pn), transpiration rate (Tr), and respiration (Gs) are important factors affecting crop growth and yield and are the basis of crop metabolism [45]. Water Use Efficiency (WUE) describes the relationship between the amount of water consumed by a plant during photosynthesis and the amount of carbon dioxide it fixes [16]. A reasonable amount of irrigation can protect crop photosynthetic organs and improve photosynthetic capacity [46]. In this study, mild deficit irrigation was beneficial to improve the water use efficiency of young apple trees under high fertilization conditions. Previous studies have shown that mild deficit irrigation can improve water use efficiency and maintain relatively high WUE without causing significant yield losses [47], which is due to the fact that under mild deficit irrigation conditions, the water in the soil is limited and the plant will reduce water loss by reducing transpiration, thus increasing water use efficiency.

The reasonable increase in fertilizer application was beneficial to promote crop growth. In this study, we showed that a reasonable increase in fertilizer application was beneficial to improving the Pn, Tr, Gs, and WUE of young apple trees under the same amount of irrigation. In comparison with no fertilization, the application of N and P fertilizers significantly increased the Pn, Tr, and Gs of apple leaves, as well as leaf WUE [48,49]. Some studies have shown that fertilizer deficiencies reduce crop Pn, Tr, Gs, and WUE, thus suppressing crop growth [22,50]. However, excessive fertilizer application also reduces crop yield, leaf photosynthesis, LAI, and SPAD [51,52]. Therefore, insufficient or excessive application of fertilizer will inhibit the growth of crops, and a reasonable amount of fertilizer is critical to crop growth. Verma et al. [53] showed by the effect of water-fertilizer coupling on sugarcane that under deficit irrigation treatment, a reasonable increase of Si fertilizer was beneficial to increase Gs, Tr, and SPAD of sugarcane and could significantly improve the photosynthetic capacity of sugarcane. Li et al. [23] identified that increasing fertilizer application significantly improved the photosynthetic capacity and water conductivity of young mango trees, thus improving crop water use efficiency and promoting crop growth, mainly due to the high water and fertilizer content and uniform distribution of crop roots under drip irrigation conditions [54], which allowed the roots to fully absorb water and nutrients and improve crop physiological activity, thereby increasing photosynthetic intensity [55].

4.4. Correlations among Growth, Leaf Area, Dry Matter (DM), and Physiological Indicators of Young Apple Plants under Coupled Water and Fertilizer Conditions

The crop growth indicators can better reflect their physiological indicators, which is important for the study of physiological and biochemical indicators such as Pn, Tr, and Gs of crops under conditions of adversity stress [56]. In this study, the plant growth and leaf area of young apple trees showed better linear relationships with Pn, Tr, Gs, water consumption, and WUE. There was also a better linear relationship between end-product dry matter and plant growth, leaf area, SPAD, Pn, Tr, Gs, water consumption, and WUE of young apple trees. Previous studies showed a better linear relationship between the growth and leaf area of young apple trees and Pn, Tr, and Gs, respectively [57]. There was a better linear relationship between dry matter and yield and water consumption of young apple trees [39]. This shows that the growth and dry matter of young apple trees under different water-fertilizer coupling systems are closely related to these indicators, and to some extent, the growth indicators of the crop can reflect its physiological characteristics.

5. Conclusions

Reasonable water and fertilizer regulation has a positive effect on the growth and physiological characteristics of young apple trees. In this study, under the same irrigation conditions, moderate increases in fertilizer application were able to increase plant growth, basal stem growth, leaf area, SPAD value, dry matter, photosynthetic rate, stomatal conductance, and water-use efficiency of young apple trees, and the maximum values could be reached under the high fertilizer treatment F1 (27-9-9 g N-P_2O_5-K_2O). However, mild deficit irrigation was more beneficial to apple growth than sufficient irrigation under the F1 treatment. Young apple trees showed the best physiological and growth conditions in the F1W2 (mild deficit irrigation W2 (65–80% Fs) + high fertilization F1) treatment. F1W2 in 2019 and 2020 obtained the maximum dry matter of 543.3 g plant^{-1} and 654.1 g plant^{-1}, which increased by 0.8–42.8% in 2019 and 0.6–40.0% in 2020 compared with other treatments, respectively. Therefore, the F1W2 treatment is the best water-fertilizer coupling model for young apple trees in semi-arid regions of northern China.

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