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Plant Photosynthesis and Dry Matter Accumulation Response of Sweet Pepper to Water–Nitrogen Coupling in Cold and Arid Environment

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Abstract: In order to optimize the water and nitrogen management mode and realize the efficient scale production of sweet pepper, from 2021 to 2022, field experiments on sweet pepper cultivation with different water and nitrogen coupling modes were conducted in the Hexi Oasis irrigation areas. The regulation effects of the water–nitrogen coupling mode on the dry matter accumulation characteristics, photosynthesis, yield, and water–nitrogen utilization efficiency of sweet pepper were further discussed. Irrigation was set for full irrigation (W1, 75–85% FC [field capacity]), mild (W2, 65–75% FC), and moderate (W3, 55–65% FC) water deficit levels. Three levels of nitrogen were applied, high (N1, 300 kg·ha^{-1}), medium (N2, 225 kg·ha^{-1}) and low (N3, 150 kg·ha^{-1}), with full irrigation and no nitrogen application used as the control (CK). The results showed that the appropriate water–nitrogen coupling mode could enhance the photosynthetic rate, increase dry matter accumulation and the accumulation rate, advance the days of a maximum rate of dry matter accumulation, and improve yield and water–nitrogen utilization efficiency. N1W1 had the greatest dry matter accumulation, the mean rate and the maximum increase rate of dry matter accumulation in sweet pepper, which was not a significant difference from N2W2, but significantly increased by 19.61%, 19.67%, and 23.45%, respectively, compared with CK. Water deficit significantly advanced the days of a maximum rate of dry matter accumulation. The days of a maximum rate of dry matter accumulation appeared 1.18–5.79 days earlier at W3 than at W2 and W1, and the maximum rate appeared gradually later with increasing irrigation. The net photosynthetic rate, the transpiration rate, and stomatal conductance of N2W2 sweet pepper showed the best performance at all growth stages, significantly increasing by 23.87%, 27.71%, and 27.39%, respectively, compared with CK. Moreover, the Intercellular CO_2 concentration was significantly reduced by 14.77% in N2W2 compared to CK. The N2W2 had the highest yield, water use efficiency, and irrigation water use efficiency of sweet pepper, significantly increasing 26.89%, 33.74%, and 31.22% compared to CK. Excessive water and nitrogen dosage reduced nitrogen partial factor productivity, while an appropriate increase in irrigation under reduced nitrogen conditions facilitated the water nitrogen potential. Passage path analysis further showed that water–nitrogen coupling promotes plant biomass formation and distribution by increasing photosynthetic assimilation capacity, ultimately increasing yield. Therefore, the N2W2 treatment (65–75% FC, 225 kg·ha^{-1}) is the ideal water and nitrogen mode for obtaining higher yields and water and nitrogen use efficiency of sweet pepper in a cold and arid environment.

Keywords: water and nitrogen coupling; photosynthesis; dry matter accumulation characteristics; water and nitrogen utilization efficiency; sweet pepper

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1. Introduction

The proliferation of water scarcity, flooding, and soil erosion in the context of global climate change has greatly affected and changed the spatial and temporal patterns of agricultural production factors, threatening global food security [1,2]. Water resources are the lifeblood roots that sustain food security and strategic resources that support countries and regions' sustainable and healthy economic, social and ecological development [3]. At present, during China's drought and water shortage, with agriculture as a major water user, water scarcity is still a rigid constraint on its sustainable development [4]. The Hexi Oasis region's rich natural resources and unique climatic conditions provide favorable crop growth conditions. However, with the development of the local economy and urban scale in this area, agricultural water use has been continuously compressed and squeezed, and the contradiction between the limited water supply and the increasing water demand is becoming more and more prominent [5]. In addition, the high consumption and low−efficiency pattern of nitrogen fertilizer input has aggravated the deterioration of soil properties and the ecological environment in the region [6]. As a result, improving water and nitrogen use efficiency and developing precise and efficient agriculture are urgently needed to promote healthy and sustainable agricultural development in the region.

Sweet pepper (*Capsicum annuum* L.), a genus of peppers in the Solanaceae family, is a subspecies capable of bearing sweet-tasting berries. As one of the essential bulk vegetables for annual domestic supply, sweet pepper has both nutritional value and medicinal potential [7]; it is rich in natural bioactive substances such as ascorbic acid, carotenoids, flavonoids, organic acids, phenolic compounds, and capsaicin [8]. It has antioxidant, antibacterial and anti-inflammatory and antimutagenic effects/anti-cancer activity, and it is capable of promoting functional properties such as cardiovascular and gastrointestinal health and enhancing human immunity [9]. Sweet peppers' yield and quality are regulated by genetics and closely related to external environmental factors such as climate, soil condition, and agronomic measures. They are susceptible to soil moisture and nutrients [10]. Sweet pepper grows better under suitable temperatures, water and fertilizer, while will be significantly affected when subjected to drought and waterlogging of its poor-developed root system and weak growth ability. Therefore, irrigation and nitrogen application are the key factors affecting yield formation and quality of sweet pepper [11].

Irrigation and nitrogen are essential factors affecting crop growth and development as well as necessary means of effectively enhancing farm productivity [12]. Traditionally, high crop yields depend on significant water and fertilizer inputs, increasing the undesired output of water resources and exacerbating soil nutrient beneficiation, nitrogen deposition, and deterioration of soil properties [13,14]. Numerous studies showed that 95% of crop dry matter accumulation was derived from organic matter produced by photosynthesis [15], and the photosynthetic rate was the basis of biological yield formation. In contrast, the crop photosynthesis and dry matter accumulation characteristics were closely related to soil water level and nutrient availability [16]. Crop leaf transpiration flux and stomatal opening are regulated by the atmospheric environment, soil water potential, and endogenous plant signaling hormones, which can induce better root uptake for soil water and mineral nutrients in maintaining normal physiological functions of aboveground plant organs [17]. Excessive soil moisture not only affects soil water heating and aeration but also weakens the plant's resistance to stress, while severe soil water stress affects crop growth by directly reducing cell division and tissue expansion in plant organs. Excessive water deficit also reduces leaf stomatal conductance, leaf water potential, and CO_2 diffusion in leaf sarcolemmal cells, inhibits photosynthetic enzymes, causes photo−oxidative stress on photosynthetic organs, and affects leaf carbon assimilation capacity [18,19]. However, mild water stress during crop growth and development is beneficial to the regulation of leaf stomatal number increase and opening degree as well as stomatal spatial distribution pattern, which can both significantly reduce extravagant transpiration of crops without sacrificing photosynthetic product accumulation and improve water use efficiency [20]. Nitrogen is another critical factor affecting the yield of sweet pepper. The addition of exogenous nitrogen at low soil nitrogen levels significantly affects soil nitrogen accumulation, promoting plants' ability to take up and assimilate nutrients. In contrast, soil nitrogen content can become saturated when nitrogen is applied excessively or continuously, and the nitrogen surplus exacerbates soil and plant nitrogen load, which in turn reduces crop productivity [21,22]. Numerous research has shown a significant coupling effect between water and nitrogen, with the two promoting and inhibiting each other. A suitable amount of water increased the nitrogen harvest index. Improper water and nitrogen application can result in limited accumulation of SPAD and uncoordinated distribution of photosynthetic products [23]. This will inhibit the transfer of nutrients to the plant's reproductive organs, ultimately reducing crop yield and water and nitrogen use efficiency [24]. The appropriate amount of nitrogen both reduces the redundant growth of stems and leaves in the pre-growing period and inhibits plant growth excessively in the late growth period, which in turn promotes the transfer of photosynthetic assimilation products to reproductive organs and effectively mitigates and compensates for the effects of water stress on crop yield [25–27].

However, most of the studies mentioned above have been mainly focused on wheat [28], rice [29], maize [30], cucumber [31], and tomato [32] crops. There are still significant deficiencies in research on optimizing multi-objective water and nitrogen management and quantifying critical thresholds of water and nitrogen for sweet pepper. Therefore, the objectives of the present study were to determine: (1) the effects of water and nitrogen coupling under-film drip irrigation on photosynthetic characteristics, dry matter accumulation, yield, and water and nitrogen use efficiency of sweet pepper and (2) the optimal water and nitrogen coupling mode for sweet pepper planting in a cold and arid environment.

2. Materials and Methods

2.1. Experimental Site

This experiment was performed from May to September 2021 to 2022 at the Yimin Irrigation Experiment Station in Minle County, Zhangye City, Gansu Province (Figure 1). The experimental station is located at the eastern end of the Hexi Corridor (38°390′ N, 100°430′ E) in Gansu Province. The mean altitude of the experimental station is 1970 m, typical of a continental desert steppe climate. The average annual precipitation and evaporation are 200 and 1638 mm, respectively. The annual sunshine hours are approximately 3000 h, the mean multi-year temperature is 7.6 °C, the mean frost-free period is 109–174 days, and the light and heat resources are abundant. The mean rainfall for the experimental periods of 2021 and 2022 was 183.5 mm and 216.2 mm, respectively. The farmland soil type is light loam. The field water holding capacity of the 0–60 cm soil layer is 24% (gravimetric moisture content), and the soil bulk density is approximately 1.46 $g\cdot cm^{-3}$. The contents of the soil organic matter, alkaline decomposed nitrogen, available potassium and available phosphorus contents in the 0–20 cm soil layer were 11.3 $g\cdot kg^{-1}$, 57.3 $mg\cdot kg^{-1}$, 191.7 $mg\cdot kg^{-1}$ and 15.9 $mg\cdot kg^{-1}$, respectively. The groundwater level was below 20 m, and there was no salinization effect. The mean temperature and rainfall during the sweet pepper growing season are shown in Figure 2.

2.2. Experimental Design and Method

The variety of sweet pepper for testing was the Qiemen sweet pepper, bred by the Gansu Wuwei Dadi Seed Industry Co., Ltd. (Wuwei, China). Sweet peppers were transplanted and planted on 9 May 2021 and 11 May 2022 at the experimental site and harvested in four crops from 12 July to 29 August. The planting density of sweet pepper was 46,500 plants per hectare. The experimental plots were mechanically plowed to 30 cm depth and mechanically weeded before planting. The basal fertilizer application was 40% of the total designed amount of nitrogen (urea, N content 46.4%), with diammonium phosphate (P_2O_5 content 46%) of 90 $kg\cdot ha^{-1}$, potassium sulfate of (K_2O content 52%) 110 $kg\cdot ha^{-1}$, and 60% nitrogen fertilizer was applied at a ratio of 4:3:3 during blossoming and fruiting and full fruiting. Two drip irrigation belts (spaced at a distance of 80 cm) were laid in each plot. The average dropper flow and dropper spacing were 2.4 $L\cdot h^{-1}$ and 30 cm, respectively. A pressure water meter with an accuracy of ±2% was used to control the irrigation volume. Colorless plastic mulch with a width of 120 cm was used for overlapping full mulch and covered with 5 cm of fine soil. A 60 cm depth of plastic film was buried between neighboring plots to prevent water and fertilizer penetrating each other.

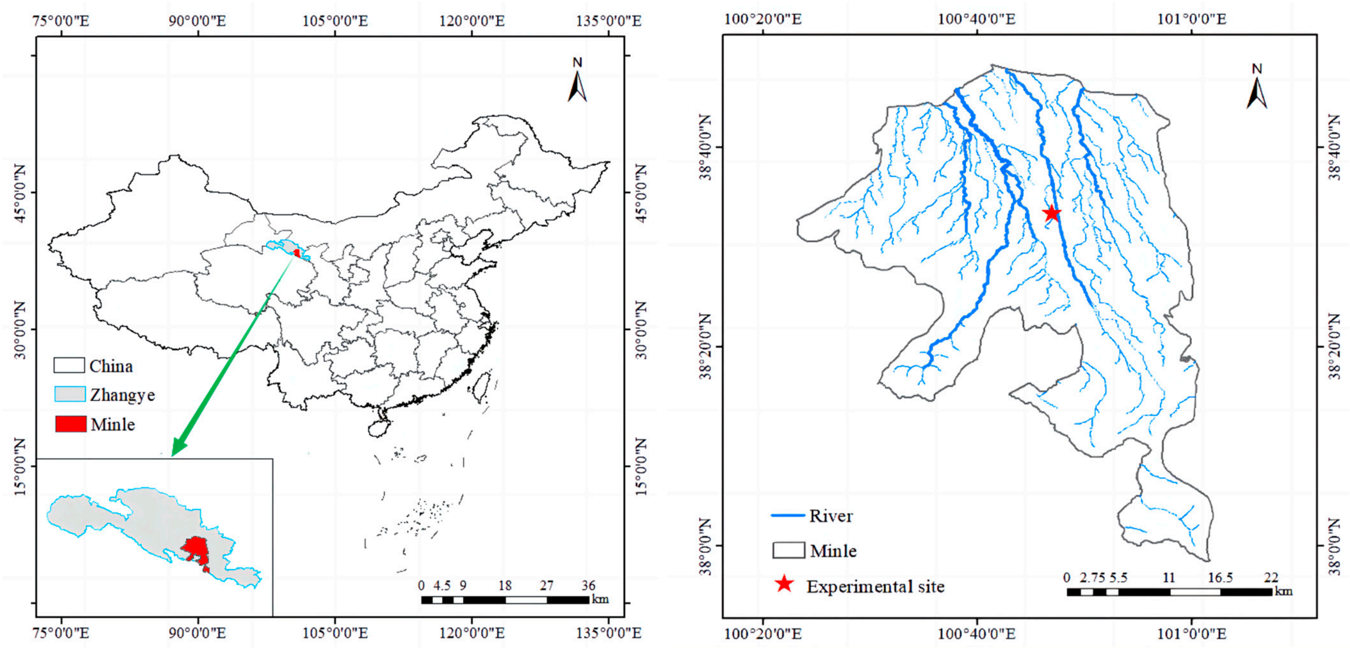

Figure 1. Location of the experimental site.

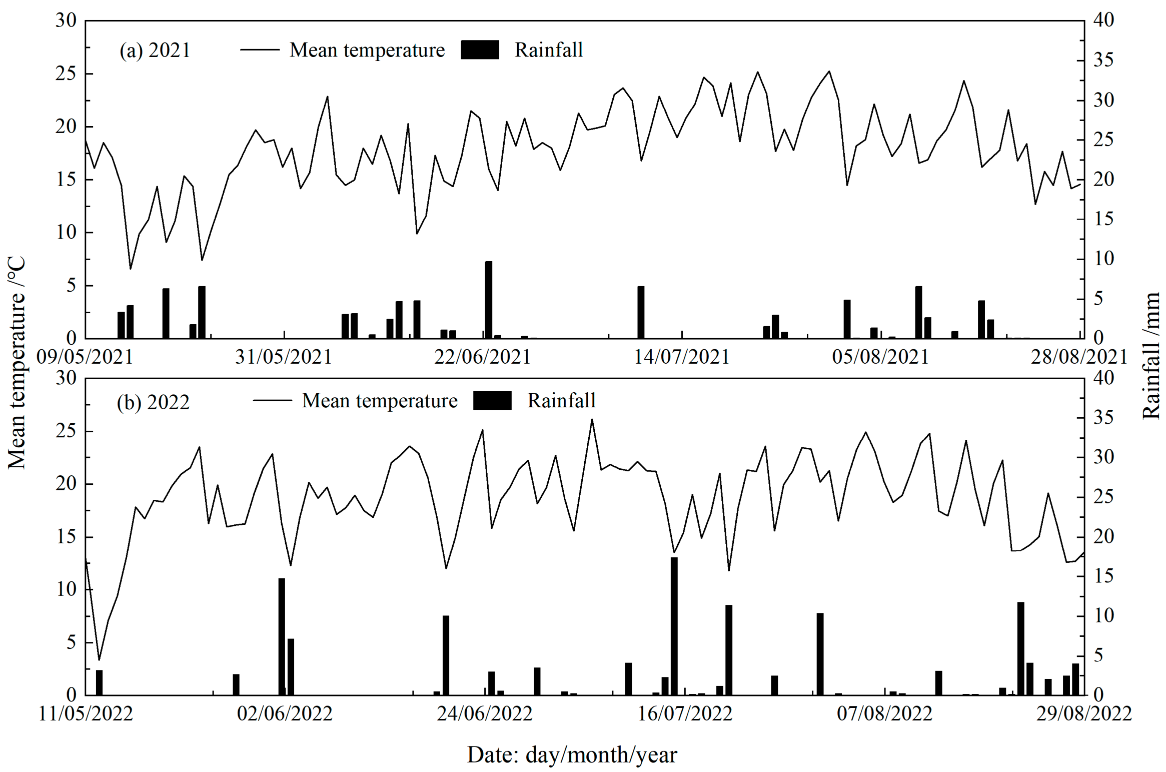

Figure 2. Rainfall and mean temperature during the growth periods in 2021 and 2022.

A two−factor randomized block design was used in the experiment. The growing season of sweet pepper was divided into four stages: seedling, blossoming and fruiting, full fruiting, and later fruiting (Table 1). Irrigation was supplied with three water gradients, which were set for full irrigation (W1, 75–85% FC [field capacity]), mild (W2, 65–75% FC), and moderate (W3, 55–65% FC) water deficit during the whole growing season. Three levels of high (N1, 300 kg·ha^{-1}), medium (N2, 225 kg·ha^{-1}), and low (N3, 150 kg·ha^{-1}) nitrogen application were maintained, with full irrigation and no nitrogen application used as the control (CK). A total of 10 treatments were established with three replications, and the plot area was 8.6 m^2 (2 m × 4.3 m). Two ridges of sweet pepper were planted in each plot, with a ridge width of 70 cm, ridge height of 25 cm, and ridge spacing of 40 cm. Each ridge was arranged in a band of double row control, with both sweet pepper planting row spacing and plant spacing of 40 cm. The soil moisture content in the 0–60 soil layer was monitored in each plot every ten days to regulate the water deficit. When the soil moisture content dropped to the lower limit of the design moisture, a certain amount of irrigation water was to be applied immediately. The specific irrigation time and irrigation amount as shown in Figure 3.

Table 1. Experiment design of water and nitrogen coupling at different growth stages of sweet pepper.

Treatments	Nitrogen Application	Relative Soil Water Content (%FC)			
		Seedling	Blossoming and Fruiting	Full Fruiting	Later Fruiting
CK	0	75–85	75–85	75–85	75–85
N1W1	300	75–85	75–85	75–85	75–85
N1W2	300	65–75	65–75	65–75	65–75
N1W3	300	55–65	55–65	55–65	55–65
N2W1	225	75–85	75–85	75–85	75–85
N2W2	225	65–75	65–75	65–75	65–75
N2W3	225	55–65	55–65	55–65	55–65
N3W1	150	75–85	75–85	75–85	75–85
N3W2	150	65–75	65–75	65–75	65–75
N3W3	150	55–65	55–65	55–65	55–65

Notes: The values at the ends of the horizontal lines indicate the upper and lower limits of the relative soil moisture content (percent field capacity).

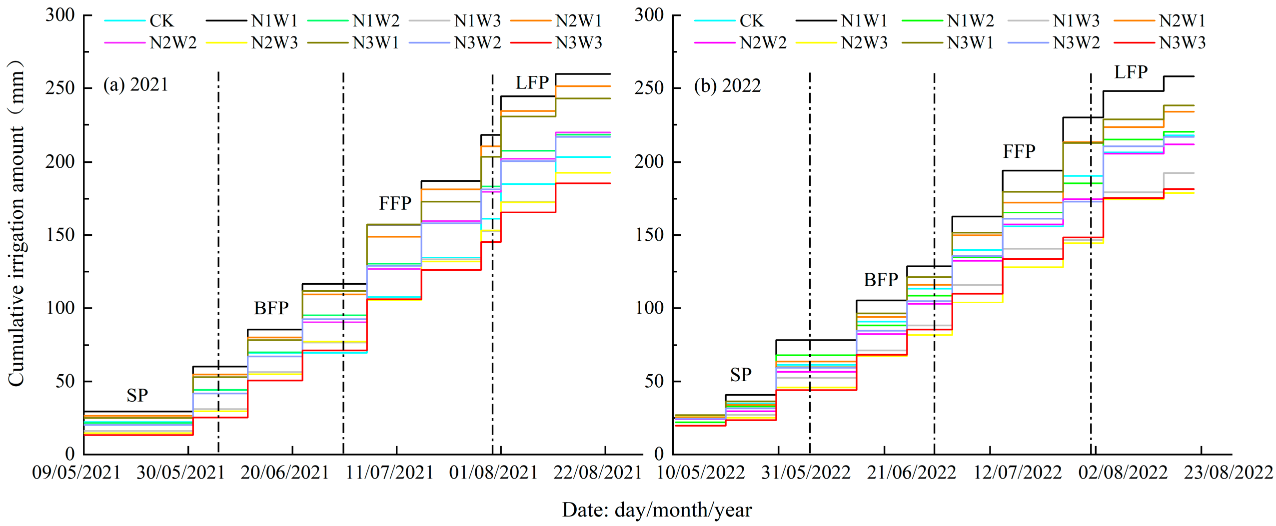

Figure 3. Irrigation timing and volume in 2021 and 2022. SP, seedling; BFP, blossoming and fruiting; FFP, full fruiting; LFP, later fruiting.

2.3. Measurements and Calculations

2.3.1. Photosynthetic Physiological Indices

The photosynthetic indexes of sweet pepper were measured using an LI−6400 portable photosynthesis instrument (LI−COR, Lincoln, NE, USA). A clear, cloudy and windless day was selected for each growing season. Three sweet pepper plants were selected randomly arbitrarily in each plot, with the top second leaf as the measurement point. Photosynthetic parameters such as the net photosynthetic rate (Pn), the transpiration rate (Tr), stomatal conductance (Gs) and intercellular CO_2 concentration (Ci) were measured from 9:30 a.m. to 10:30 a.m., and the results were averaged.

2.3.2. Dry Matter Accumulation

Three sweet pepper plants were selected randomly for destructive sampling in each plot at each growth stage. The plant samples' above-ground and root parts were washed and treated, removing the moisture with filter paper. After weighing, each organ of the plant was packed into paper bags and quickly placed in a preheated 105 °C oven, which was set to 85 °C after 30 min. After 24 h, the samples were removed and weighed, and the dry matter accumulation was calculated as Equation (1):

$$\text{Dry matter accumulation} = \text{dry matter accumulation of single plant} \times \text{planting density} \tag{1}$$

To better reveal the effect of water and nitrogen coupling on sweet pepper's dry matter accumulation characteristics, a logistic model was fitted to analyze it [33].

a. Logistic model equation

$$y = \frac{k}{1 + a \times e^{-bt}} \tag{2}$$

b. A first-order derivative of the equation obtains the growth rate equation.

$$V = \frac{a \times b \times k \times e^{-bt}}{\left(1 + a \times e^{-bt}\right)^2} \tag{3}$$

c. The maximum growth rate ($kg \cdot d^{-1} \cdot ha^{-1}$) and the days (d) are obtained by taking the first-order derivative of the growth rate equation and making it zero.

$$V_{\max} = \frac{k \times b}{4} \tag{4}$$

$$T_{\max} = \frac{Ln\ a}{b} \tag{5}$$

d. By taking the second−order derivative of the growth rate equation and setting it to zero, two inflection points, T_2 and T_3, can be obtained on the growth curve. The gradual increase stage of dry matter accumulation after transplantation and planting sweet pepper to T_2, T_2 to T_3 is the rapid increase stage, and T_3 to the end of the growing season is the slow increase stage.

$$T_2 = \frac{Ln\ a - 1.317}{b} \tag{6}$$

$$T_3 = \frac{Ln\ a + 1.317}{b} \tag{7}$$

The above equation is where *k* is the limiting value of dry matter accumulation, and *a* and *b* are the fixed coefficients of the model.

2.3.3. Fruit Yield

All pickings were weighed and yield per plant was measured. The average value from three replications was used for each treatment as the yield value and ultimately converted to the production value per hectare.

2.3.4. Water and Nitrogen Utilization Efficiency

Water use efficiency, irrigation water use efficiency and nitrogen partial factor productivity are calculated as follows:

$$WUE = Y/ET \quad (8)$$

$$IWUE = Y/I \quad (9)$$

$$NPFP = Y_N/F_N \quad (10)$$

where *WUE* is water use efficiency (kg·ha^{-1}·mm^{-1}), *IWUE* is irrigation water use efficiency (kg·ha^{-1}·mm^{-1}), and *NPFP* is nitrogen partial factor productivity (kg·kg^{-1}). For calculating *WUE*, *Y* is the yield of sweet pepper per unit area (kg·ha^{-1}) and *ET* is the total water consumption during the growing season (mm). For calculating *IWUE*, *I* is the total amount of irrigation water per unit area throughout the growing season (mm). For calculating *NPFP*, Y_N is the yield per unit area of sweet pepper in the nitrogen application area and F_N is nitrogen application per unit area (kg·ha^{-1}).

2.4. Statistical Analysis

Microsoft Excel 2019 (Microsoft Corp., Raymond, WA, USA) was used for calculation and pre−processing of the experimental data. SPSS 25.0 software (IBM, Inc., New York, NY, USA) was used for analysis of significance, correlation, and regression analyses. If a significant difference was observed (p < 0.05), Tukey's HSD comparison was adopted. Graphs were graphed using Origin 2021 software (Origin Lab., Corp., Hampton, MA, USA).

3. Results

3.1. Photosynthetic Characteristics

3.1.1. The Net Photosynthetic Rate

Photosynthetic intensity and accumulation of photosynthetic products were closely related to the net photosynthetic rate (Pn). The Pn of sweet pepper showed a unimodal variation curve during the whole growing season (Figure 4). Pn showed a gradually increasing trend from seedling to full fruiting period, reaching a maximum at full fruiting period, while that in the later fruiting period began to decrease in each treatment. Pn increased most during the sweet pepper's blossoming and fruiting period, significantly higher than during the seedling and later fruiting period. Compared to the 2–year average Pn results, each growth season of sweet pepper showed similar Pn variations. Medium nitrogen level was better than high nitrogen, low nitrogen, and CK at the same irrigation level. Compared to N3W1 and CK, Pn increased significantly (p < 0.05) by 12.40% and 20.42% in N2W1 but not significantly (p > 0.05) between N2W1 and N1W1. Compared to N3W2, the Pn of N2W2 increased significantly by 13.55% but not significantly between N2W2 and N2W1. Compared with N1W3 and N3W3, the Pn of N2W3 it was increased significantly by 4.53% and 18.40%, respectively. A mild water deficit at the same nitrogen application level increased sweet pepper leaf Pn. The Pn in W2 and W1 levels were not significantly different, but W2 was higher than W3 levels and increased significantly by 16.60–21.57%. A 2-year average Pn for sweet pepper was highest in W2N2, followed by W1N2, but this difference was insignificant. Compared to CK, W2N2 significantly increased Pn by 28.37%, while the increase over other treatments was 2.70–38.05% in N2W2. Sweet pepper harvests higher Pn under mild water deficit conditions during the growing season with appropriate nitrogen application, which lays the foundation for organic matter accumulation and transport in the plant.

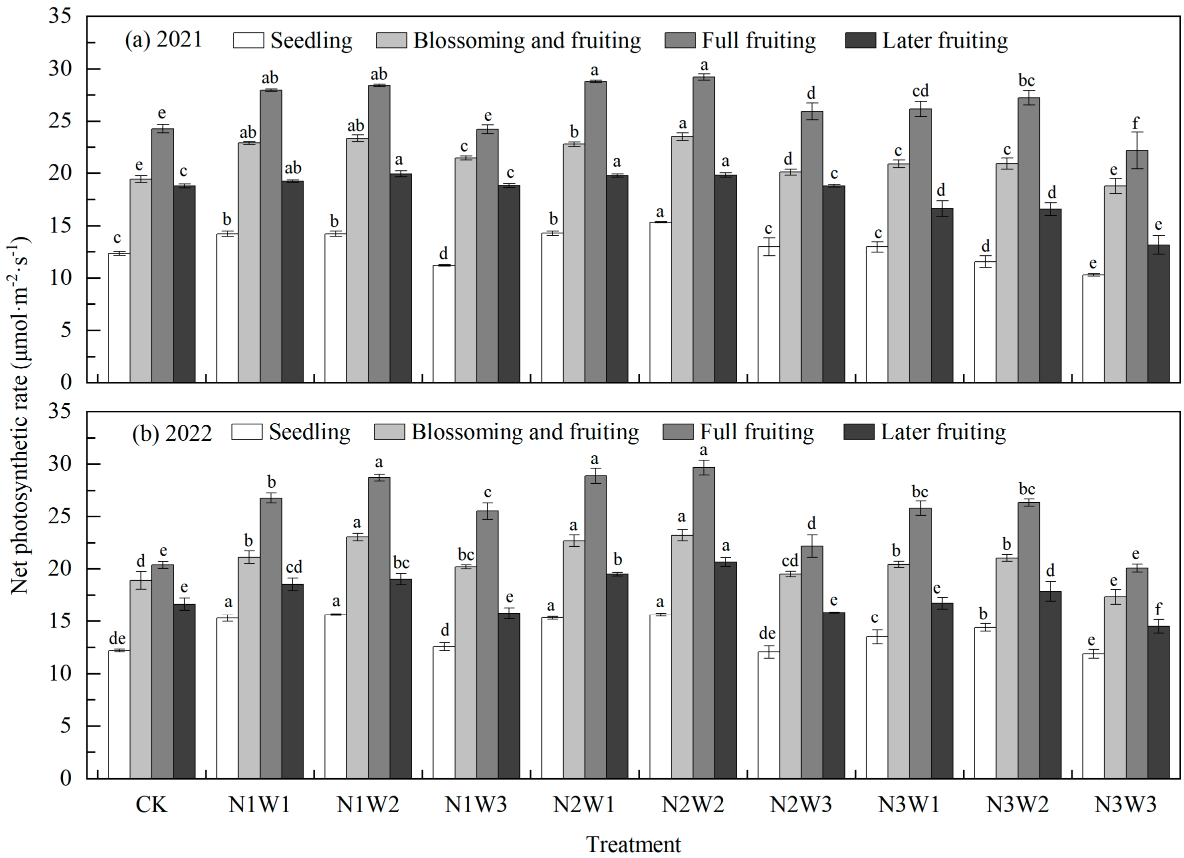

Figure 4. Net photosynthetic rate under different water and nitrogen coupling modes. Different lowercase letters indicate significant differences at the $p < 0.05$ level. The same as below.

3.1.2. The Transpiration Rate

The sweet pepper transpiration rate (Tr) increased during the growing season, followed by a decrease (Figure 5). Tr increased most during the blossoming and fruiting period, peaking during the growing season, while Tr gradually declined after full fruiting in each treatment. Tr was the smallest for all treatments at the seedling period, averaging 4.81 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and significantly ($p < 0.05$) different among treatments. During the blossoming and fruiting period, N1W2 had the largest Tr of 11.99 $\mu mol \cdot m^{-2} \cdot s^{-1}$, which was not significantly ($p > 0.05$) different from N2W2. Tr saw no significant decrease with mild water and nitrogen deficits during the blossoming and fruiting period, and Tr was more sensitive to water than nitrogen application during this period. Sweet pepper Tr decreased with moderate water deficits. Tr was significantly reduced in N1W3, N2W3, and N3W3 by 21.06%, 21.66%, and 30.85% compared to N1W2 and by 0.52%, 1.28%, and 12.86%, respectively, compared to CK. The Tr was second only to the blossoming and fruiting period in the full fruiting period. Tr was optimum for fruiting in N2W2 and was not significantly different from Tr in N1W1, N1W2, and N2W1. CK and N3W3 were significantly lower than N2W2 by 22.80% and 33.78%, respectively. During the later fruiting period, Tr decreases significantly compared to the blossoming and fruiting and full fruiting period. Moreover, with increasing water and nitrogen application at the same level of water and nitrogen deficits, Tr increased and then decreased. Sweet pepper Pn was highest in W2N2, which was not significantly different from N1W1, N1W2, and N2W1, but was significantly higher than CK by 30.15%. Based on the above results, nitrogen application and irrigation significantly affect Tr. Moderate water deficits and low nitrogen treatments significantly reduced Tr. Medium nitrogen application levels increased Tr during full irrigation and mild water deficit conditions at whole growth stages.

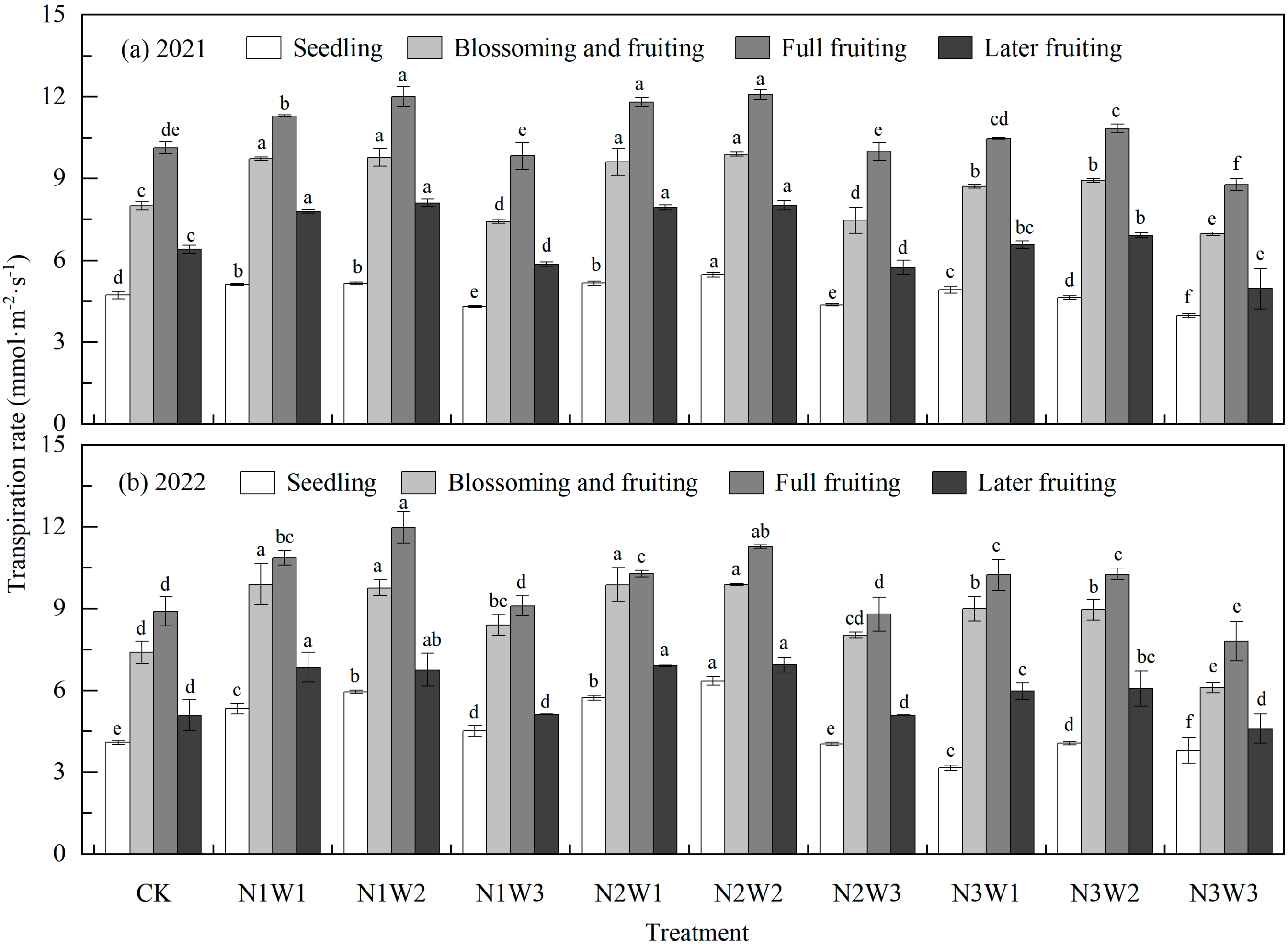

Figure 5. Transpiration rate of sweet pepper under different water and nitrogen coupling modes.

3.1.3. Stomatal Conductance

Stomata are significant outlets for water vapor during transpiration and gas exchange channels during photosynthesis and respiration. During the exchange of gases between plants and the atmosphere, water and nitrogen deficits reduce mesophyll cells' turgor pressure. This leads to a deterioration in leaf stomatal shape and ultimately reduces stomatal conductance (Gs). As the growing season progressed, Gs gradually increased with each treatment and peaked at the full fruiting period. The Gs decreased gradually as the treatments entered the later fruiting period (Figure 6). Small Gs were in each water and nitrogen coupling treatment at the seedling period but varied significantly ($p < 0.05$). N2W2 had the largest Gs, not significantly ($p > 0.05$) different from N1W1, but significantly increased than CK by 61.08%. There are similar Gs trends during the blossoming and fruiting period and the full fruiting period. Gs showed an increase then decrease tendency with increasing nitrogen application and irrigation at the same level of irrigation and nitrogen application. The N1 and N2 nitrogen levels remained relatively high under W1 and W2 irrigation. The N2W2 had the highest Gs, at an average of 0.359 mol·m^{-2}·s^{-1}, a significant increase of 41.08% compared to CK. Compared with the blossoming and fruiting period and the full fruiting period, Gs was significantly lower in each treatment during the later fruiting period. The difference between N1 and N2 Gs levels was insignificant at the same irrigation level, but it increased by 7.24% and 7.58%, respectively, compared to N3, and by 14.55% and 14.90%, respectively, compared to CK. The difference in Gs between W1 and W2 levels at the same nitrogen application level was insignificant, but it increased by 24.23% and 25.17%, respectively, compared to N3. According to these results, water and nitrogen regulation significantly influence Gs in sweet pepper, with both high and low water and nitrogen supplies reducing Gs.

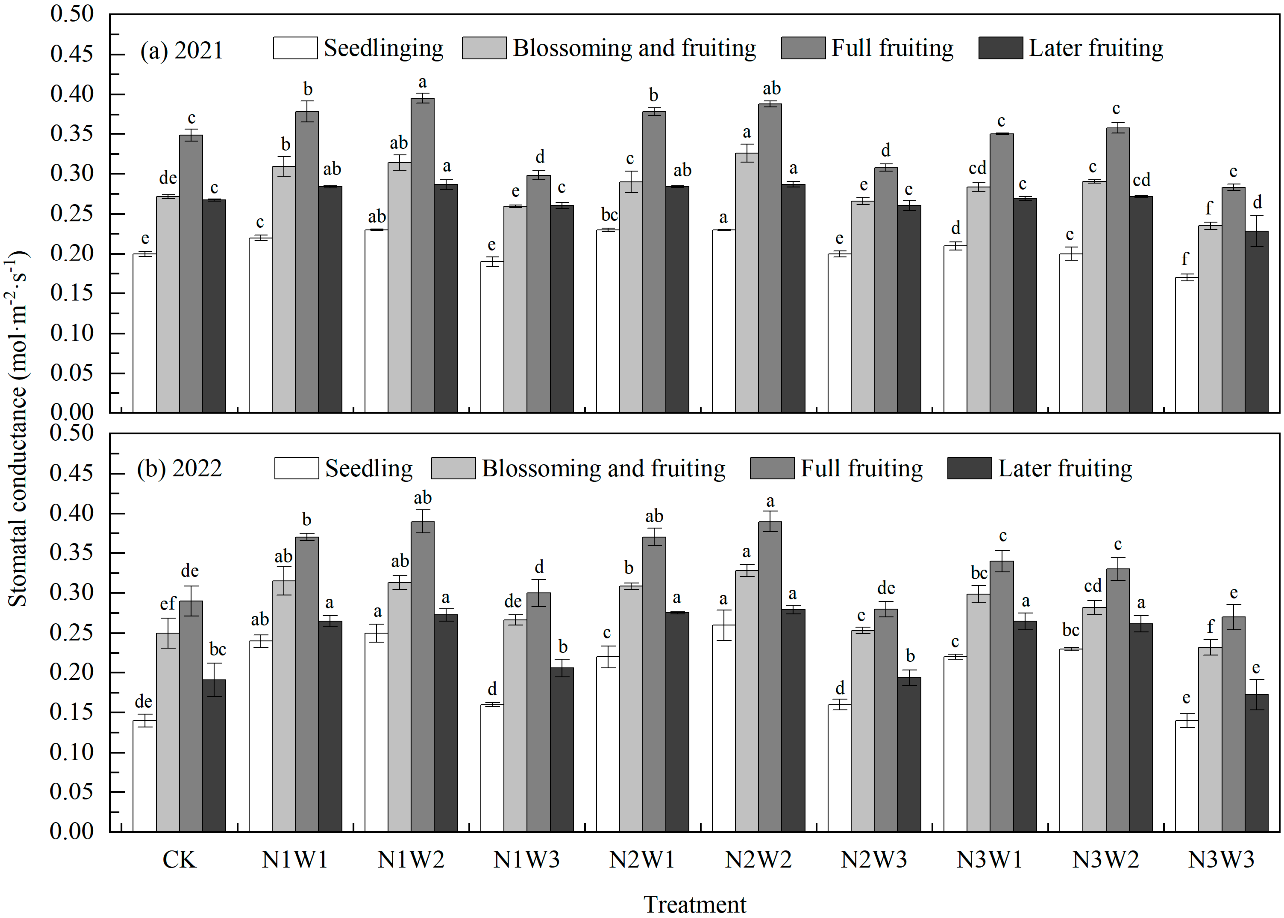

Figure 6. Stomatal conductance of sweet pepper under different water and nitrogen coupling modes.

3.1.4. Intercellular CO_2 Concentration

During the growing season, the intercellular CO_2 concentration (Ci) was the opposite variation of Pn, Tr, and Gs, with a V-shaped pattern of decrease followed by an increase (Figure 7). The Ci averaged 236.64 μmol·m^{-2}·s^{-1} during the seedling period, which was the highest. As the growing season progressed, Ci gradually decreased and reached its lowest value during the full fruiting period, averaging 179.78 μmol·m^{-2}·s^{-1}. During the later fruiting period, Ci gradually increased. According to the two-year average Ci results, Ci variation was similar across each water and nitrogen treatment throughout the growing season. Compared to N1, N2 levels had the lowest Ci at the same irrigation level, with a non-significant ($p > 0.05$) reduction of 0.35–1.89%. Furthermore, the Ci of N2 was significantly reduced by 5.49–22.77% compared to N3 and significantly ($p < 0.05$) declined by 8.96% compared to CK on average. Hence, a mild nitrogen deficit can maintain a low Ci level. With increasing irrigation levels, Ci decreased and then increased at the same nitrogen application level. While W1 and W2 levels kept low Ci, the difference was insignificant. Compared to W3, W1, and W2 levels showed significant differences in decreases of 12.23–15.79% and 14.78–16.12%, respectively. This indicates that full irrigation and mild water deficit can reduce Ci during the growth period, with mild water deficit resulting in a more significant reduction.

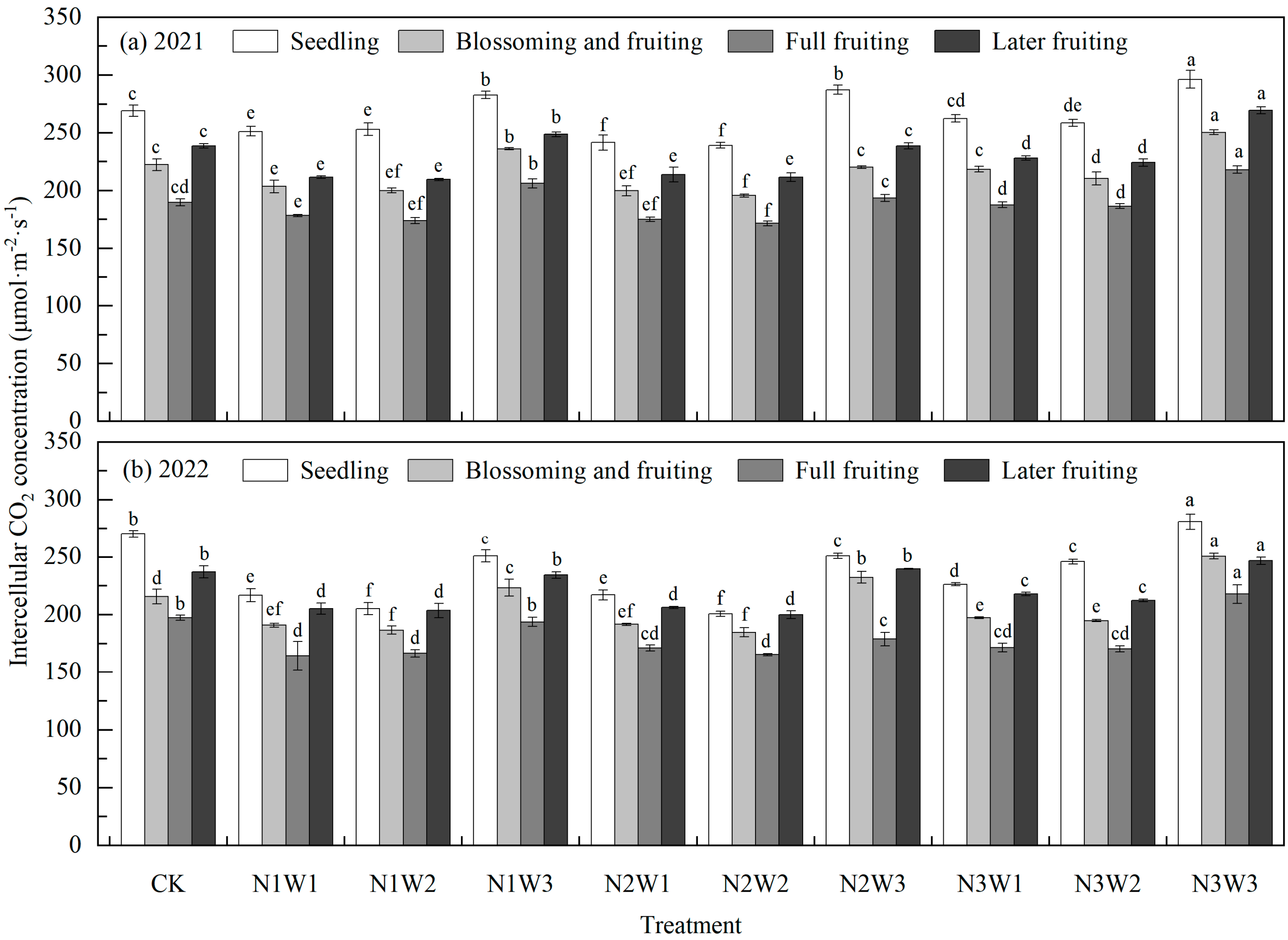

Figure 7. Intercellular CO_2 concentration of sweet pepper under different water and nitrogen coupling modes.

3.2. Dry Matter Accumulation Characteristics

3.2.1. Dry Matter Accumulation

The irrigation level and nitrogen application significantly affected the entire growing season of sweet pepper dry matter accumulation (Figure 8). Dry matter accumulation dynamics showed an S-shaped growth curve under different water and nitrogen modes, reaching a maximum under each treatment at the later stage of fruiting. Dry matter accumulation increased with increasing irrigation levels and nitrogen application at each growing season. There was the most significant dry matter accumulation in N1W1, followed by N2W2, and the least in N3W3. Compared with N1W1, N2W2's two-year average dry matter accumulation was reduced by 0.95–2.38%, which was insignificant ($p > 0.05$). Compared to N1W1, N3W3, and CK were significantly ($p < 0.05$) reduced by 45.73–63.13% and 19.38–35.40%, respectively. This indicates that an appropriate reduction in irrigation and nitrogen application does not significantly affect dry matter accumulation. Moreover, excessive water deficit and low or no nitrogen was not satisfying for sweet pepper's normal growth and development, which eventually showed a decrease in dry matter accumulation. Under conditions of full irrigation or mild water deficit, an appropriate increase in nitrogen application is beneficial to the accumulation of dry matter in sweet peppers, laying the foundation for high yields.

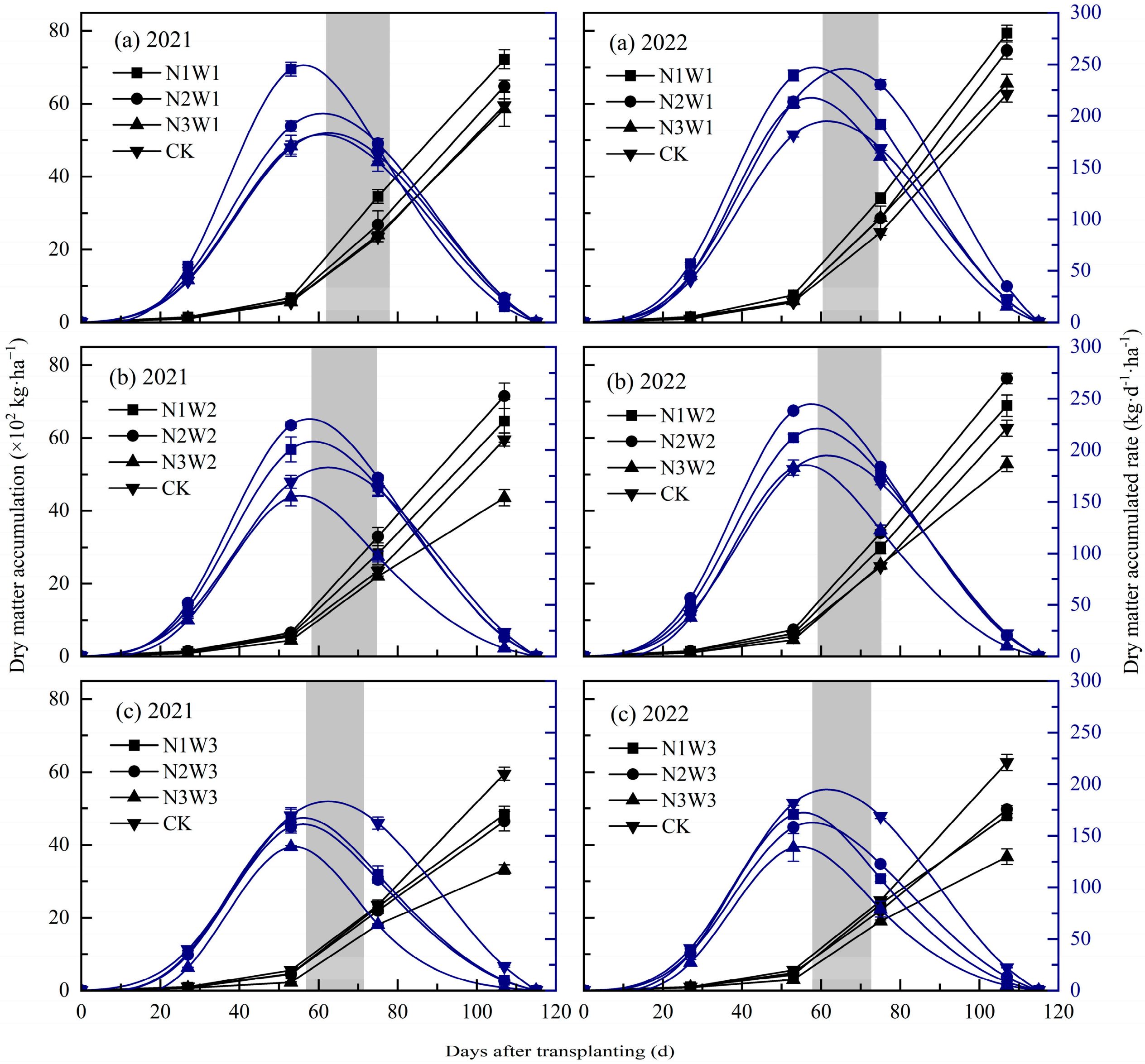

Figure 8. Dry matter accumulation dynamics of sweet pepper under different water and nitrogen coupling. The shaded part of the graph indicates the days of occurrence and duration of the maximum rate of dry matter accumulation.

3.2.2. The Dry Matter Accumulation Rate

The 2-year mean dry matter accumulation rate tends to increase and decrease as the growing season progresses, reaching a maximum during the full fruiting period (Figure 8). With increased irrigation level and nitrogen application, sweet pepper's mean dry matter accumulation rate increased significantly throughout its growth stage. According to the regularity of dry matter accumulation in sweet pepper, dry matter accumulation can be divided into gradual, rapid, and slow increasing stages. Irrigation level, nitrogen application and water–nitrogen interaction significantly affected the mean dry matter accumulation rate for each stage (Table 2).

Table 2. Characteristics of dry matter accumulation in sweet pepper.

Year	Treatment	Gradual Increase Stage		Rapid Increase Stage		Slow Increase Stage	
		DT/d	MD/(kg·d^{-1}·ha^{-1})	DT/d	MD/(kg·d^{-1}·ha^{-1})	DT/d	MD/(kg·d^{-1}·ha^{-1})
2021	CK	46.75 a	69.03 d	33.18 a	174.80 d	32.07 e	74.49 c
	N1W1	44.40 a	91.09 a	29.78 b	232.32 a	37.81 bcd	93.24 a
	N1W2	45.43 a	77.78 c	31.59 ab	197.48 c	34.97 de	81.43 b
	N1W3	44.38 a	61.04 e	29.64 b	155.76 e	37.98 bc	62.42 d
	N2W1	46.19 a	76.04 c	32.85 a	192.51 c	32.96 e	81.24 b
	N2W2	44.94 a	85.38 b	31.09 ab	216.92 b	35.96 cd	88.61 a
	N2W3	44.38 a	58.71 e	29.50 a	149.89 e	38.12 bc	59.98 d
	N3W1	46.10 a	68.37 d	32.95 b	172.96 d	32.96 e	73.05 c
	N3W2	43.58 a	56.14 e	29.32 b	143.14 e	39.11 b	56.98 d
	N3W3	44.48 a	49.07 f	24.74 c	127.28 f	42.78 a	49.20 e
2022	CK	46.81 ab	73.50 c	32.23 a	186.88 c	31.96 d	78.49 d
	N1W1	44.98 b	91.91 a	31.74 ab	232.91 a	34.27 cd	95.95 b
	N1W2	45.59 b	82.58 b	31.76 ab	209.63 b	33.66 cd	86.71 c
	N1W3	44.21 b	62.35 e	28.75 cd	159.58 e	38.04 a	63.35 f
	N2W1	48.74 a	92.35 a	32.80 a	235.45 a	29.46 e	101.42 a
	N2W2	44.68 b	90.55 a	31.42 ab	229.57 a	34.90 bc	94.02 b
	N2W3	45.02 b	60.32 e	31.06 ab	153.30 e	34.91 bc	62.63 f
	N3W1	45.40 b	80.73 b	30.11 bc	206.17 b	35.49 bc	83.44 c
	N3W2	44.74 b	67.80 d	28.90 cd	173.66 d	37.35 ab	69.19 e
	N3W3	44.17 b	49.90 f	27.34 e	128.36 f	39.49 a	50.37 g

Notes: Values followed by different letters within a column are significantly different at $p < 0.05$. The same as below. DT, duration of characteristic periods of dry matter accumulation; MD, mean dry matter accumulation rate.

During the rapid increase stage, full irrigation and light water deficits are more conducive to increasing the dry matter accumulation rates under the same nitrogen application. N1W1 and N1W2 showed significant ($p < 0.05$) increases by 47.53% and 29.10%, respectively, in the mean dry matter accumulation rates compared to N1W3. Compared to N2W3, the mean dry matter accumulation rates in N2W1 and N2W2 increased significantly by 41.15% and 47.26%, respectively. Compared to N3W3, the mean dry matter accumulation rates in N3W1 and N3W2 increased significantly by 48.30% and 28.92%, respectively. Compared with N3W1, the mean dry matter accumulation rates in N1W1 and N2W1 increased significantly by 22.71% and 12.88%, respectively, and increased significantly by 28.63% and 15.49% compared to CK, respectively, at the same irrigation level. The dry matter accumulation rates for N1W2 and N2W2 were significantly higher than those for N3W2, at 23.82% and 40.94%, respectively. Moreover, N1W3 and N2W3 were significantly higher than those for N3W3, at 23.35% and 18.60%, respectively. Dry matter accumulation rates varied similarly during the gradual and slow increases stages. The mean dry matter accumulation rate of N1W1 was higher than that of N3W3 and CK by 84.46% and 26.03%, respectively, but not significantly ($p > 0.05$) different from that of N2W2. This indicates that increasing nitrogen application significantly enhanced dry matter accumulation rates at each growth stage under full irrigation and mild water deficit conditions. Furthermore, increasing irrigation levels effectively mitigated the effect of low nitrogen stress on sweet pepper dry matter accumulation rates.

3.2.3. Logistic Model Equation Fitting the Maximum Increase Rate and Days of Dry Matter Accumulation

Regression analysis showed that the relationship between dry matter accumulation (Y) and days after transplantation (t) could be fitted by the logistic equation $Y = k/(1 + ae^{-bt})$. The F-test of the model equation was highly significant ($p < 0.01$), with $R^2 > 0.994$, indicating that the logistic equation fitting pepper's dry matter accumulation process was reasonable and reliable. We obtained the maximum increase rate and the days of dry matter accumulation from the model equation.

Irrigation level and nitrogen application significantly affected the maximum increase rate of dry matter accumulation; nitrogen application had a non−significant effect on the days of a maximum rate of dry matter accumulation (Table 3). At the same nitrogen application, the maximum increase rate of dry matter accumulation in N1W1 and N1W2 was significantly ($p < 0.05$) higher by 47.53% and 27.10%, respectively, compared to N1W3. In contrast, the days of a maximum rate of dry matter accumulation in N1W3 was 1.18 d and 2.45 d earlier than N1W1 and N1W2, respectively. The maximum increase rate of dry matter accumulation was significantly increased in N2W1 and N2W2 by 41.14% and 47.26% compared to N2W3, while the days of a maximum rate of dry matter accumulation in N2W3 occurred 2.36 d earlier than in N1W1, respectively. The maximum increase rate of dry matter accumulation was significantly increased in N3W1 and N3W2 by 48.30% and 29.92% compared to N3W3, while the days of a maximum rate of dry matter accumulation in N3W3 occurred 4.16 d earlier than in N3W1, respectively. At the same level of irrigation, the maximum increase rate of dry matter accumulation was significantly increased by 22.71% and 12.88% for N1W1 and N2W1 compared to N3W1 and significantly increased by 28.63% and 12.56% compared to CK, respectively. The maximum increase rate of dry matter accumulation was significantly increased by 28.50% and 40.94% for N1W2 and N2W2 compared to N3W2 and significantly increased by 23.35% and 18.60% for N1W3 and N2W3 compared to N3W3, respectively. Among all treatments, the maximum increase rate of dry matter accumulation was most remarkable in N1W1, which was not significantly different from N2W2 but was increased significantly than CK by 28.63%. Moreover, excessive water and nitrogen deficits advance the days of a maximum rate of dry matter accumulation, with N3W3 advancing the days by 5.79 d compared to CK. This indicates that a mild water deficit coupled with a medium nitrogen application can maintain peak dry matter accumulation without significantly reducing the maximum increase rate, thereby increasing total dry matter accumulation.

Table 3. Logistic equation regression analysis of dry matter accumulation dynamics in sweet pepper.

Year	Treatment	Regression Equation	R^2	DM/d	MR/(kg·d^{-1}·ha^{-1})
2021	CK	$y = 105.4675/[1 + 152.7580exp(-0.07939t)]$	0.9999 **	63.34 a	199.36 d
	N1W1	$y = 125.8319/[1 + 189.4544exp(-0.08844t)]$	0.9997 **	59.30 ab	264.97 a
	N1W2	$y = 113.4659/[1 + 164.7848exp(-0.08337t)]$	0.9997 **	61.23 ab	225.23 c
	N1W3	$y = 83.9666/[1 + 192.6368exp(-0.08886t)]$	0.9998 **	59.20 ab	177.65 e
	N2W1	$y = 114.9941/[1 + 151.5540exp(-0.08019t)]$	0.9998 **	62.61 a	219.56 c
	N2W2	$y = 122.6659/[1 + 168.0023exp(-0.08471t)]$	0.9997 **	60.49 ab	247.41 b
	N2W3	$y = 80.4147/[1 + 196.3542exp(-0.08929t)]$	0.9999 **	59.13 ab	170.96 e
	N3W1	$y = 103.6271/[1 + 148.7734exp(-0.07995t)]$	0.9999 **	62.57 a	197.26 d
	N3W2	$y = 76.3106/[1 + 187.2143exp(-0.08985t)]$	0.9998 **	58.23 ab	163.25 e
2022	N3W3	$y = 57.2609/[1 + 425.4876exp(-0.10648t)]$	0.9995 *	56.85 c	145.17 f
2022	CK	$y = 109.5280/[1 + 171.19746exp(-0.08173t)]$	0.9999 **	62.92 ab	213.14 c
	N1W1	$y = 134.45317/[1 + 155.9884exp(-0.0829t)]$	0.9998 **	60.86 bc	265.64 a
	N1W2	$y = 121.0691/[1 + 163.6797exp(-0.08294t)]$	0.9997 **	61.47 abc	239.08 b
	N1W3	$y = 83.4313/[1 + 214.3845exp(-0.09162t)]$	0.9996 **	58.59 c	182.00 e
	N2W1	$y = 140.4546/[1 + 186.9313exp(-0.0803t)]$	0.9998 **	65.14 a	268.54 a
	N2W2	$y = 131.1786/[1 + 158.0301exp(-0.08383t)]$	0.9998 **	60.39 bc	261.83 a
	N2W3	$y = 86.6077/[1 + 169.7551exp(-0.08479t)]$	0.9999 **	60.55 bc	174.84 e
	N3W1	$y = 112.8918/[1 + 197.9960exp(-0.08748t)]$	0.9999 **	60.45 bc	235.14 b
	N3W2	$y = 91.2836/[1 + 220.16147exp(-0.06441t)]$	0.9997 **	59.19 bc	198.06 d
	N3W3	$y = 63.8251/[1 + 263.04775exp(-0.09634t)]$	0.9995 **	57.84 c	146.40 f
		Significance (F value)			
Irrigation level W		—	—	5.9671 **	385.978 **
Nitrogen level N		—	—	2.3310	133.632 **
W × N		—	—	1.3891	18.1187 **

Notes: * means significant difference ($p < 0.05$), ** means extremely significant difference ($p < 0.01$). MR, maximum increase rate of dry matter accumulation; DM, the days of a maximum rate of dry matter accumulation. The same as below.

3.3. Fruit Yield and Water and Nitrogen Utilization Efficiency

3.3.1. Fruit Yield

Sweet pepper yields were significantly affected by irrigation levels and nitrogen application (Table 4). With the same level of irrigation, sweet pepper yield increased and then decreased as nitrogen levels increased and N2 levels yields were optimal. N2W1 yielded significantly ($p < 0.05$) 9.43%, 12.99%, and 18.47% more than N1W1, N3W1, and CK, respectively. N2W2 yielded significantly more than N1W2 and N3W2 by 14.10% and 20.77%, respectively. N3W2 yielded significantly more than N3W3 by 23.73%, but not significantly ($p > 0.05$) compared to N1W3. A mild water deficit is more conducive to higher sweet pepper yields at the same nitrogen application level. N1W2 was not significantly different from N1W1, but the yield was significantly increased at 19.58% compared to N1W3. Compared to N2W1 and N2W3, N2W2 yielded significantly more at 7.10% and 34.54%, respectively. There was no significant difference in yield between N3W2 and N3W1, but N3W2 yielded a significant 37.85% more than N3W3. N2W2 showed the highest yield of all treatments, significantly higher than N1W1, N3W3, and CK by 17.21%, 66.47%, and 26.89%, respectively. Consequently, appropriate water deficit and nitrogen reduction measures do not significantly affect sweet pepper growth but also contribute to increased yield.

Table 4. The yield, WUE, IWUE and NPFP of sweet pepper under different treatments.

Year	Treatment	Yield/(kg·ha^{-1})	WUE/(kg·ha^{-1}·mm^{-1})	IWUE/(kg·ha^{-1}·mm^{-1})	NPP/(kg·kg^{-1})
2021	CK	35,033.33 cd	13.17 cde	15.09 cd	—
	N1W1	36,733.33 cd	12.53 e	14.13 de	122.44 c
	N1W2	38,100.00 bc	15.16 b	17.45 b	127.01 c
	N1W3	33,533.33 d	14.90 b	17.42 b	111.79 c
	N2W1	41,000.00 ab	14.41 bc	16.31 bc	182.22 b
	N2W2	43,758.33 a	17.31 a	19.92 a	194.49 b
	N2W3	33,666.67 d	14.96 b	17.52 b	149.62 c
	N3W1	35,658.33 cd	12.9 de	14.68 de	237.70 a
	N3W2	35,366.67 cd	14.15 bcd	16.29 bc	235.78 a
	N3W3	24,733.33 e	11.33 f	13.36 e	164.89 c
2022	CK	37,170.44 e	12.40 de	16.28 e	—
	N1W1	41,431.57 cd	12.67 de	16.77 de	138.11 e
	N1W2	42,192.97 c	14.16 b	19.58 b	140.64 e
	N1W3	33,612.40 f	12.18 ef	17.63 cd	112.04 f
	N2W1	44,538.67 b	14.53 b	18.98 b	197.95 c
	N2W2	47,858.07 a	16.86 a	21.24 a	212.70 b
	N2W3	34,430.11 f	13.09 cd	19.21 b	153.02 d
	N3W1	40,044.91 d	12.80 cde	16.81 de	266.97 a
	N3W2	40,495.79 d	13.39 c	18.52 bc	267.75 a
	N3W3	30,301.40 g	11.57 f	16.56 de	202.01 c
Significance (F value)					
Irrigation level W		235.973 **	66.194 **	52.351 **	208.281 **
Nitrogen level N		71.489 **	52.443 **	41.153 **	833.675 **
W × N		7.604 *	8.216 **	5.402 **	21.493 **

Notes: * means significant difference ($p < 0.05$), ** means extremely significant difference ($p < 0.01$).

3.3.2. Water Use Efficiency and Irrigation Water Use Efficiency

Irrigation level and nitrogen application significantly influenced water use efficiency (WUE) and irrigation water use efficiency (IWUE). WUE and IWUE were highest in N2W2, followed by N1W2. Compared to CK, the WUE of N2W2 and N1W2 were significantly ($p < 0.05$) increased by 33.74% and 16.79%, while their IWUE significantly increased by 31.22% and 18.01%, respectively. N3W3 had the smallest WUE and IWUE, with significant reductions of 30.44% and 27.32%, respectively, compared to N2N2. WUE and IWUE increased and then decreased with increasing irrigation levels and nitrogen application under the same water and nitrogen levels. As irrigation levels and nitrogen application reach W2 and N2, continued water and nitrogen dosage increases do not increase yield significantly and significantly reduce WUE and IWUE.

3.3.3. Nitrogen Partial Factor Productivity

Nitrogen partial factor productivity (NPFP) is a crucial indicator of nitrogen fertilizer output efficiency during crop production. N3W1 had the largest NPFP, followed by N3W2, which were not significantly ($p > 0.05$) different. N1W3 had the smallest NPFP, significantly ($p < 0.05$) lower at 55.65% and 55.55% compared to N3W1 and N3W2. As nitrogen application increased at the same irrigation level, NPFP decreased. Compared to N3W1, N1W1 and N2W1, it significantly lowered NPFP by 48.37% and 24.67%, respectively. Compared to N3W2, N1W2 and N2W2 were significantly reduced by 46.85% and 19.13%, respectively. Compared to N3W3, N1W3 and N2W3 were reduced by 38.99% and 17.51%, respectively. NPFP increased and then decreased with increasing irrigation levels at N1 and N2 nitrogen application levels, while NPFP increased with increasing irrigation levels at N3 nitrogen application. The difference in NPFP between W1 and W2 irrigation levels was not significant. This indicates that excessive irrigation and nitrogen application resulted in a decrease in NPFP. An appropriate increase in irrigation under reduced nitrogen conditions is conducive to realizing water and nitrogen potential, thus achieving water savings, nitrogen reduction and yield increase.

3.4. Path Analysis

Figure 9 shows the correlations between the critical indicators for sweet peppers. There was a significant correlation between dry matter accumulation and the net photosynthetic rate (Pn), the transpiration rate (Tr), stomatal conductance (Gs) and the maximum increase rate of dry matter accumulation (MR), with correlation coefficients ranging from 0.833 to 0.992, and a significant negative correlation with intercellular CO_2 concentration (0.880 **). NPP was not significantly correlated with photosynthetic and dry matter accumulation dynamics indicators. A significant and positive correlation existed between water use efficiency and Pn (0.780 **). Sweet pepper yield was significantly positively correlated with Pn, Tr, Gs, DMA and MR, with correlation coefficients ranging from 0.797 to 0.941, while it was significantly negatively correlated with intercellular CO_2 concentration (0.950 **).

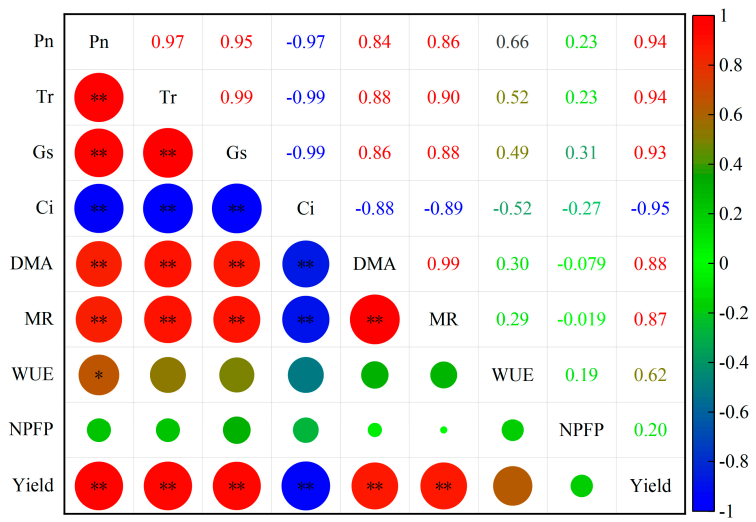

Figure 9. Correlation analysis between the main indicators of sweet pepper under coupled water and nitrogen conditions. DMA, dry matter accumulation; MR, maximum increase rate of dry matter accumulation. * means significant difference ($p < 0.05$), ** means extremely significant difference ($p < 0.01$).

In order to explore the effect of the variables on pepper yield, stepwise regression analysis, significance tests, and the elimination of unnecessary variables were used to establish the best−fit equation for yield (Y) and the independent variable X:

$$Y = -5442.178 + 1885.519X_1 + 1.024X_2 \left(R^2 = 0.882, p < 0.05\right)$$

where Y is the yield of sweet pepper (kg·ha^{-1}); X_1 is the net photosynthetic rate (μmol·m^{-2}·s^{-1}); X_2 is the dry matter accumulation in the later fruiting period (kg·ha^{-1}).

Pn has a direct path coefficient of 0.705 with yield, while the indirect path coefficient of Pn to yield through dry matter accumulation was 0.226 (Table 5). Dry matter accumulation has a direct path coefficient of 0.268 with yield, while the indirect path coefficient of dry matter accumulation to yield through Pn was 0.595. Based on the above analysis, dry matter accumulation is an essential indicator for evaluating sweet pepper yields, and the net photosynthetic rate can be used as a key indicator for assessing yield. This also indicates that water and nitrogen coupling enhances photosynthetic assimilation capacity and promotes biomass formation and distribution in the plant, which increases yield. Furthermore, the coefficient of determination for the equation above is 0.882, while the residual factor e is 0.336. This indicates that in addition to the two above independent variables, some factors that are not considered significantly impact sweet pepper yield. Further research is required to analyze sweet pepper yield factors comprehensively.

Table 5. Path analysis of sweet pepper yield with the net photosynthetic rate and dry matter accumulation.

Index	Single Correlation Coefficient	Direct Path Coefficient	Indirect Path Coefficient	
			X_1→Yield	X_2→Yield
Net photosynthetic rate X_1→	0.941 **	0.705	–	0.226
Dry matter accumulation X_2→	0.875 **	0.268	0.595	–

Note: ** means extremely significant difference (p < 0.01).

4. Discussion

4.1. The Effects of Water and Nitrogen Coupling on Sweet Pepper Photosynthesis and Dry Matter Accumulation

This study indicated that a mild water deficit coupled with medium nitrogen significantly improves sweet pepper's photosynthesis and dry matter accumulation dynamics. Pn, Tr and Gs of sweet pepper tended to increase and then decrease with increasing irrigation levels and nitrogen application, while the opposite trend was observed for Ci. This result indicates that sweet pepper photosynthesis was affected by the level of water and nitrogen application. compared to the conventionally irrigated nitrogen application, which was no significant difference in leaf SPAD values or photosynthetic index yields between the 25% nitrogen-reducing and 20% water-saving treatments [34]. Severe water and nitrogen deficits disrupt plant source and sink balance, affecting photosynthetic product accumulation, translocation, and distribution [35]. Increasing irrigation and nitrogen application can significantly increase the crop photosynthetic rate and dry matter accumulation. However, the photosynthetic rate gradually decrease when water and nitrogen quotas exceed a particular range [36]. An appropriate water and nitrogen deficit balanced soil water and nitrogen content, facilitating water and air exchange in sweet pepper leaves. Moreover, appropriate water and nitrogen dosage increased leaf stomatal traits and CO_2 fixation capacity, greatly enhancing sweet pepper photosynthetic physiological activity [37].

An excessive water and nitrogen supply causes redundant growth of nutrient organs and affects pre-flowering dry matter translocation. Consequently, the sink-source ratio increases, resulting in a reduction in the rate of production and translocation of photosynthetic products [38]. Conversely, insufficient water and nitrogen can cause the demand for assimilation by the sink to exceed the loading capacity of the source, resulting in forced translocation and distribution, which in turn causes premature leaf failure [39]. This study showed that the dry matter accumulation rate and dry matter accumulation of N2W2 were not significantly different from N1W1 and were significantly higher than CK by 19.67% and 21.08%. This indicates that increasing water and nitrogen application increases sweet pepper dry matter accumulation, but weakens photosynthesis in the leaves during growth periods, reducing sink competitiveness in reproductive organs. A suitable water and nitrogen deficit can give the plant some resistance exercise and facilitate the tilt distribution of photosynthetic products to the sink [40]. This study also found that an appropriate increase in nitrogen application significantly increased the maximum increase rate of dry matter accumulation. The days of a maximum rate of dry matter accumulation occurred significantly earlier with water deficit and moved backward gradually with increasing irrigation levels. This indicates that increasing water and nitrogen level increases the maximum increase rate of dry matter accumulation but is not conducive to maintaining peak dry matter accumulation [41]. A mild water deficit and medium nitrogen coupling maintain a high rate of dry matter accumulation while delaying the peak dry matter accumulation, thus enhancing the duration of photosynthesis [42].

4.2. The Effects of Water and Nitrogen Coupling on Sweet Pepper Yield and Water and Nitrogen Utilization Efficiency

This study showed that as irrigation levels and nitrogen application increased, sweet pepper yield, WUE, and IWUE tended to increase and then decrease. The yield and WUE/IWUE did not significantly improve with further irrigation or nitrogen application increases at 65–75% FC and 225 kg·ha^{-1}. This indicated that mild water and nitrogen deficits benefit sweet pepper yield and WUE. On the one hand, a mild water and nitrogen deficit was conducive to plant root extension and efficient absorption of soil moisture and nutrients [43]. On the other hand, it can effectively harmonize sink-source relationships, promote photosynthetic product distribution, and avoid excessive water–nitrogen consumption in the plant [44]. Sweet pepper yields tend to rise quadratically with increasing irrigation, and either too high or too low irrigation inhibits yield formation and reduces water and nitrogen use efficiency [45]. Water deficits during critical periods will cause a reduction in production, while timely nitrogen application can alleviate water deficits' effect on yield [46]. Analogously, both excess and deficiency of nitrogen will improve crop yields. Excessive nitrogen application prolongs crop maturity and increases susceptibility to pests and diseases. This leads to high susceptibility to plant failure in late reproduction, reducing crop productivity and fertilizer use efficiency [47]. A nitrogen deficiency inhibits the physiological activity of plant leaf mesophyll cells and reduces the content of superoxide dismutase, catalase, and SPAD in leaves [48]. This causes premature failure of crop nutrient organs due to impaired organic matter synthesis, which affects photosynthetic characteristics during the growth period and ultimately reduces crop yield [49]. This study also found that excessive water nitrogen dosage reduced NPFP, while an appropriate increase in irrigation under reduced nitrogen conditions facilitated the water nitrogen potential. This indicates that increasing irrigation water benefits NPFP improvement, but WUE and IWUE negatively correlate with irrigation water [50]. Therefore, a proportionate increase in irrigation level under reduced nitrogen conditions benefits the water and nitrogen potential [51].

5. Conclusions

The photosynthetic characteristics, dry matter accumulation dynamics, yield, and water and nitrogen utilization efficiency of sweet pepper were influenced by different degrees of water and nitrogen deficit regulation. During the growing season, mild water deficit and medium nitrogen coupling significantly increased the net photosynthetic rate (Pn), the transpiration rate (Tr), and stomatal conductance (Gs). Dry matter accumulation in sweet pepper is reduced by water and nitrogen deficits. However, the mild water deficit and medium nitrogen coupling modes, without significantly reducing dry matter accumulation, advanced the days of a maximum rate of dry matter accumulation and prolonged the duration of peak dry matter accumulation, thus promoting a coordinated distribution of photosynthetic products. Mild water deficits and medium nitrogen coupling modes significantly increased sweet pepper yield and WUE, while full irrigation, medium water deficit irrigation levels, and high and low nitrogen application levels significantly reduced sweet pepper yield and WUE. Furthermore, the path analysis revealed that sweet pepper yield was significantly and positively related to the net photosynthetic rate and dry matter accumulation following the linear equation. Therefore, the persistent mild water deficit and medium nitrogen application coupling mode during the growing season is recommended as the optimal irrigation and nitrogen strategy for sweet pepper production in a cold and arid environment. The results of this study have important implications for the cultivation and sustainable development of sweet pepper.

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