

Article

# The Effect of Fertigation on Cabbage (*Brassica oleracea* L. var. *capitata*) Grown in a Greenhouse

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**Abstract:** Understanding the response of crop growth to water and fertilizer is helpful to improve their management and use efficiency. Three water and fertilizer coupling treatments were designed to carry out a two-season trial on two cabbage (*Brassica oleracea* L. var. *capitata*) cultivars in spring and autumn in the Beijing–Tianjin–Hebei region. The irrigation timings of the three treatments were controlled by the soil moisture content of 0–20 cm soil layer. Treatment 1 ( $L_W H_F$ ): when the soil moisture content was decreased to 75% of the field capacity ( $\theta_f$ ), irrigation was carried out (i.e., the lower limit of irrigation was  $75\%\theta_f$ ), the critical soil moisture content for stopping irrigation was  $90\%\theta_f$  (upper limit of irrigation), and the nitrogen (N) application amount was 400 kg/ha; treatment 2 ( $H_W L_F$ ): the lower and upper limits of irrigation were  $85\%\theta_f$  and  $100\%\theta_f$ , respectively, and the N application amount was 200 kg/ha; and treatment 3 ( $M_W M_F$ ): the lower and upper limits of irrigation were  $75\%\theta_f$  and  $100\%\theta_f$ , respectively, and the N application amount was 300 kg/ha. The results showed that the yield and its related parameters of cabbage in spring were higher than those in autumn because of the use of different cultivars and seasons. The growth indices of  $H_W L_F$  and  $M_W M_F$  in the two seasons were larger than that of  $L_W H_F$ , and the yields of  $H_W L_F$  were the highest, 78.37 t/ha (spring) and 64.42 t/ha (autumn), respectively. The nitrogen use efficiencies (NUEs) of  $L_W H_F$  in spring and  $H_W L_F$  in autumn were the highest, 213.29 kg/kg and 391.83 kg/kg, respectively. In general, there were statistically significant differences in the cumulative increment in plant height, stem diameter and leaf area in the two-season trial, yield in autumn and NUE in spring among the three treatments. In addition, there was a significant positive linear correlation between almost all indices in different growth stages and the corresponding evapotranspiration ( $ET_i$ ). It is suggested that the application of drip irrigation under mulch should be approximately 114.7–125.0 mm, and the N fertilization should be about 200 kg/ha.

**Keywords:** water and fertilizer coupling; yield; water productivity; total nitrogen uptake; nitrogen use efficiency; evapotranspiration

## 1. Introduction

Among many factors affecting crop growth, water and fertilizer are key factors that can be adjusted and controlled. In actual agricultural production, to obtain higher yields, excessive water use and fertilization have become standard practices, and these practices not only leach nutrients

from surface soil to deep soil, reducing water and nutrient use efficiency [1,2], but may also cause soil environmental deterioration [3,4]. To improve the efficiency of water and fertilizer use and determine the appropriate amount of water and fertilizer for crop growth, some authors have studied winter wheat [5], potato [6–8], tomato [9,10], broccoli [11,12], onion [13] and areca nut [14], among other crop species. These studies proposed that drip irrigation and fertilization can achieve higher water and fertilizer use efficiency and recommended improved water and fertilization management schemes for these crops compared with standard practices.

Water resources are extremely scarce in the Beijing–Tianjin–Hebei region, with agricultural water consumption close to 57.1% of the total. The vegetable planting area accounts for approximately 13% of the grain crop planting area, but vegetable water consumption accounts for approximately 20% of the grain crop water consumption. At present, the greenhouse vegetable planting area accounts for 58.7% of the vegetable planting area in the Beijing–Tianjin–Hebei region, and the planting area of greenhouse vegetables, water consumption and fertilization amount are increasing annually. It has been reported that the amount of nitrogen (N) fertilizer used in greenhouse vegetable production in this area is 1.3–5.8 times higher than the recommended value, and the nitrate content in groundwater of vegetable fields in some areas exceeds 37.5%–44.8% [15–17]. Although drip irrigation and fertilization are also used in some greenhouse vegetable planting, the waste of irrigation and fertilization is still very serious due to the lack of scientific and rational management of water and fertilizer. Therefore, it is of great significance to determine reasonable water and fertilizer management of greenhouse vegetables in the Beijing–Tianjin–Hebei region for regional water savings and pollution reduction.

The area of cabbage (*Brassica oleracea* L. var. *capitata*) is approximately 100,000 ha in the Beijing–Tianjin–Hebei region, ranking second among leafy vegetables. Moreover, cabbage has a large planting scale in many areas at home and abroad. Some authors have conducted studies on water and fertilizer consumption during the growth period of *Brassica* species. Due to differences in climate, soil physical properties and limitations of the experimental schemes, the results of different studies are different (Table 1). At present, research on cabbage has mainly been conducted in the field, and research on cabbage planting in greenhouses has been less frequently reported. In addition, research on crop biomass and N uptake and utilization has mainly focused on wheat [25,26], maize [27,28] and cotton [29], and there have also been some reports on vegetable biomass, such as tomato [30–32] and winter rape [33]. However, few reports have been put forth on the biomass allocation and nitrogen use efficiency (NUE) of cabbage in response to fertigation under mulch in greenhouses. To date, no relevant studies have been reported on the relationships between evapotranspiration ( $ET_i$ ) and the growth index of cabbage.

**Table 1.** Research results of irrigation and fertilization amounts for *Brassica*.

Serial Number	Species	Irrigation Amount (mm)	N Fertilizer Amount (kg N/ha)	Time	Research Site	Authors
1	Broccoli	–	150–200	2010	Turkey	Erdem et al. [18]
2	Cabbage	–	350–450	2004	Hefei	Guo et al. [19]
3	Cabbage	300	300	2008	Beijing	Liu et al. [20]
4	Cabbage	225	300	2014	Lanzhou	Zhang et al. [21]
5	Cabbage	204.8	304	2015	Lanzhou	Zhou et al. [22]
6	White cabbage	–	330 (included both applied N and compensation for residual mineral N in the 0–60 cm layer)	1998	Netherlands	Everaarts and De Moel [23]
7	Late cabbage	Irrigation maintained near the field capacity ( $\theta_f$ ) over the growing season	Over 400	2010	Ontario	McKeown et al. [24]

At present, most research results regarding the effect of water and fertilizer on crop growth have been carried out separately for water and fertilizer [34]. In fact, there is an incentive effect between water and fertilizer. According to relevant studies, an appropriate ratio of water and fertilizer is beneficial for increasing crop yield. The combination of high irrigation and N application may not necessarily achieve the highest yield [10,11,18], but it will certainly increase production costs. Therefore, within the recommended threshold range of published articles, water and fertilizer coupling treatments were designed in this study, and the aims were to evaluate (i) the response of different cultivars of cabbage to water and fertilizer coupling treatments, (ii) the effects of different water and fertilizer coupling treatments on cabbage growth, yield, biomass and water and nitrogen use efficiency and (iii) the relationships between  $ET_i$  and the indices at different growth stages of cabbage. The aim of this study is to propose a better water and fertilizer management model suitable for greenhouse cabbage to guide local agricultural production and to provide theoretical guidance for the rational development and utilization of water resources and the reduction of soil environmental pollution in the Beijing–Tianjin–Hebei.

## 2. Materials and Methods

### 2.1. Experimental Conditions

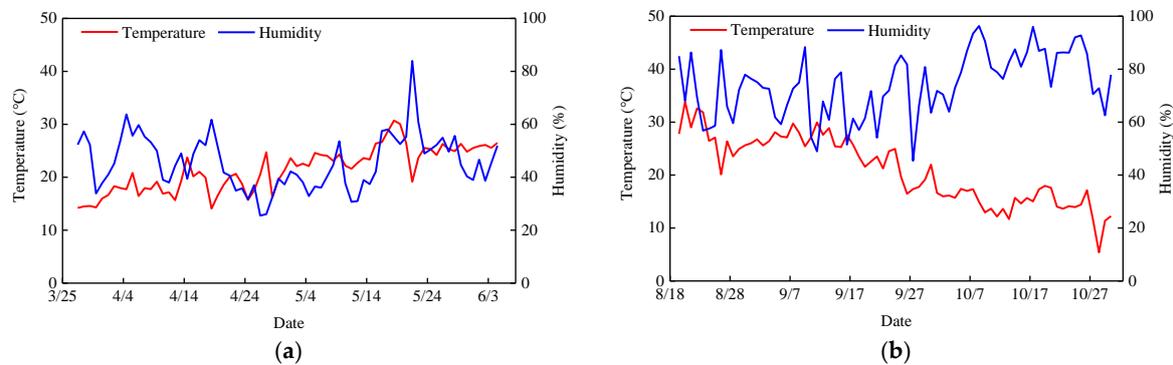
The trial was conducted in two plastic greenhouses at the water-saving irrigation demonstration base of China Irrigation and Drainage Development Center in Beijing (116°34'52" N, 40°8'20" E). The region has a warm temperate, continental semi-humid monsoon climate, with an annual mean temperature of 11.2 °C and annual mean precipitation of 625 mm. The trial was conducted in two seasons: the first trial (spring season) was conducted in the first greenhouse from March to June 2017, while the second trial (autumn season) was conducted in the second greenhouse from August to October 2017. The two greenhouses were 3 m apart. Before the beginning of the trial, soil samples were collected in each greenhouse. After air-drying, the soil samples were crushed and sifted. The particle composition of each layer was measured by a Malvern laser particle size analyzer, as shown in Table 2. Each layer of soil in the No. 1 greenhouse was a silt loam (international system). The 60–80 cm soil layer in the No. 2 greenhouse was silt, and the other layers were silt loam. In addition, the field capacity ( $\theta_f$ ) of the 1 m deep soil layer in both greenhouses varied from 0.330 cm<sup>3</sup>/cm<sup>3</sup> to 0.380 cm<sup>3</sup>/cm<sup>3</sup>, the wilting point varied from 0.151 cm<sup>3</sup>/cm<sup>3</sup> to 0.168 cm<sup>3</sup>/cm<sup>3</sup>, the bulk density was between 1.46 g/cm<sup>3</sup> and 1.61 g/cm<sup>3</sup>, and the pH value was between 7.77 and 8.66. Before the beginning of the spring trial, the initial nitrate content and ammonium content in the 0–60 cm soil layer were 65.18 mg/kg and 15.46 mg/kg, respectively.

**Table 2.** Main soil parameters of the No. 1 and No. 2 greenhouses.

Greenhouses	Soil Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Field Capacity (cm <sup>3</sup> /cm <sup>3</sup> )	Wilting Point (cm <sup>3</sup> /cm <sup>3</sup> )	Bulk Density (g/cm <sup>3</sup> )	Initial Humidity (mm)	pH
1#	0–20	7.597	77.833	14.571	0.332	0.151	1.49	55.4	8.04
	20–40	13.024	69.145	17.830	0.365	0.165	1.52	65.9	8.22
	40–60	14.127	74.314	11.559	0.377	0.167	1.58	71.7	8.30
	60–80	15.172	77.565	7.262	0.375	0.167	1.61	72.2	8.38
	80–100	15.467	70.156	14.377	0.370	0.165	1.60	72.1	8.28
2#	0–20	10.600	66.944	22.456	0.330	0.151	1.46	52.8	7.78
	20–40	16.805	78.041	5.154	0.367	0.165	1.55	58.4	7.77
	40–60	15.966	66.384	17.650	0.375	0.167	1.60	63.8	8.15
	60–80	3.253	88.219	8.528	0.380	0.168	1.59	65.1	8.40
	80–100	12.812	69.285	17.903	0.368	0.165	1.60	66.5	8.66

The daily average temperature in the greenhouses for the spring and autumn trials were 15–25 °C and 10–30 °C, respectively, and the daily air average relative humidity levels were 30%–60% and 50%–90%, respectively. The fluctuation range of the average temperature and relative humidity in

autumn was larger than that in spring, and the daily average temperature in the autumn trial was less than 20 °C starting in October, but the average relative humidity increased obviously and stayed at 75%–95% (Figure 1).



**Figure 1.** Daily average temperature and humidity in the spring trial (a); daily average temperature and humidity in the autumn trial (b).

## 2.2. Irrigation and Fertilization Treatments

Considering that the water and fertilizer coupling treatments in the trial were designed within the threshold range recommended by previously published articles [18–24], these treatments were considered to be better for cabbage growth. The purpose of this work was to select the water and fertilizer coupling scheme for cabbage growth in greenhouse in the Beijing–Tianjin–Hebei from these treatments through field comparative trial. Therefore, only three water and fertilizer coupling treatments were designed in this study.

The irrigation timing of the three treatments were controlled by soil moisture content of 0–20 cm soil layer. Treatment 1: when the soil moisture content was decreased to  $75\%\theta_f$ , irrigation was carried out (i.e., the lower limit of irrigation was  $75\%\theta_f$ ), the critical value of the soil moisture content for stopping irrigation was  $90\%\theta_f$  (upper limit of irrigation), and the N application amount was 400 kg/ha. The irrigation amount of the cabbage growth period in this treatment was the smallest compared with that of other treatments; thus, it was called the low water and high fertilizer ( $L_WH_F$ ) treatment. Treatment 2: the lower and upper limits of irrigation were  $85\%\theta_f$  and  $100\%\theta_f$ , respectively, and the N application amount was 200 kg/ha. The irrigation amount of this treatment was the largest compared with that of other treatments; thus, it was called the high water and low fertilizer ( $H_WL_F$ ) treatment. Treatment 3: the lower and upper limits of irrigation were  $75\%\theta_f$  and  $100\%\theta_f$ , respectively, and the N application amount was 300 kg/ha; thus, it was called the medium water and fertilizer ( $M_WM_F$ ) treatment. The timing and amount of the N application and the upper and lower limits of irrigation water for each treatment are shown in Table 3, and the date and amount of irrigation and fertilization are shown in Figure 2; the amount of irrigation of cabbage can be calculated by the following formula:

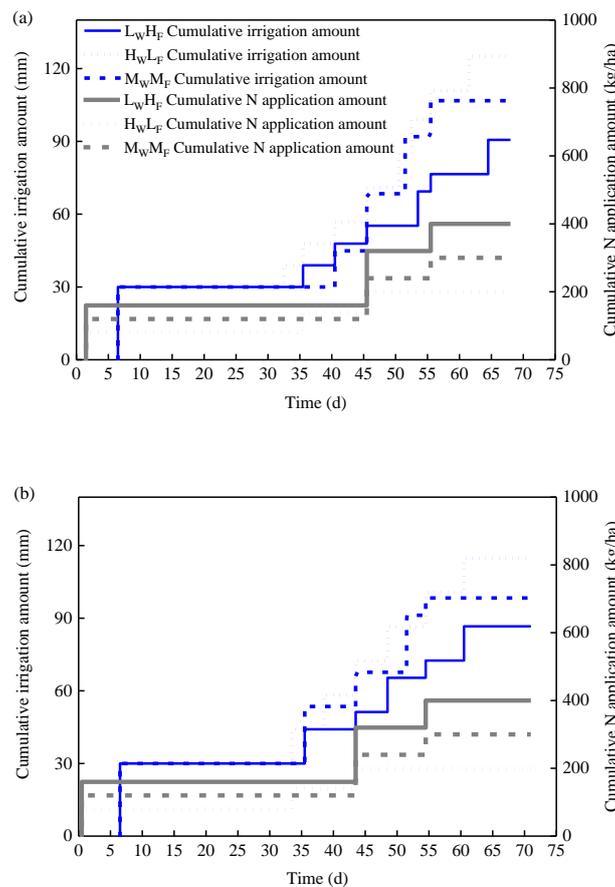
$$M = 0.1ph\theta_f(K_1 - K_2) / \eta \quad (1)$$

where  $M$  is the amount of each irrigation, mm;  $p$  is the soil moisture ratio;  $h$  is the calculated irrigation depth, 20 cm was used to calculate the irrigation depth before the early heading stage of spring cabbage, 30 cm was used after the early heading stage, and 30 cm was used during the autumn cabbage growing period;  $\theta_f$  is the calculated (volume) field capacity of the soil layer,  $\text{cm}^3/\text{cm}^3$ ;  $K_1$  and  $K_2$  are the percentages of the upper and lower limit of irrigation water to the  $\theta_f$ , respectively, %; and  $\eta$  is the utilization coefficient of irrigation water.

**Table 3.** Irrigation and nitrogen (N) application amounts for cabbage under different water and fertilizer coupling treatments.

Treatments	Irrigation				Fertilizing N amount (kg N/ha)					
	Lower Limit	Upper Limit	Single Amount (Spring) (mm)	Single Amount (Autumn) (mm)	Total (mm)	Base Fertilizer	Rosette	Early Heading	Late Heading	Total
L <sub>W</sub> H <sub>F</sub>	75% $\theta_f$ <sup>a</sup>	90% $\theta_f$	8.9 (14.1) <sup>b</sup>	14.1 <sup>c</sup>	90.6 (86.6) <sup>d</sup>	160		160	80	400
H <sub>W</sub> L <sub>F</sub>	85% $\theta_f$	100% $\theta_f$	8.9 (14.1)	14.1	125.0 (114.7)	80	60	60		200
M <sub>W</sub> M <sub>F</sub>	75% $\theta_f$	100% $\theta_f$	14.9 (23.5)	23.5	106.8 (98.3)	120		120	60	300

<sup>a</sup>  $\theta_f$  is the field capacity. <sup>b</sup> The size of the single application amount before the early heading (after the early heading) stage of cabbage in spring. <sup>c</sup> The size of the single application amount during the cabbage growing period in autumn. <sup>d</sup> Total irrigation amount of cabbage in spring (autumn).



**Figure 2.** Water and N applied in the spring cabbage growth period, with March 23 as the first day (a); water and N applied in the autumn cabbage growth period, with August 18 as the first day (b).

The same amounts of phosphorus and potassium fertilizer were applied to each treatment: 100 kg/ha (containing P<sub>2</sub>O<sub>5</sub>) and 150 kg/ha (containing K<sub>2</sub>O), respectively, of which all phosphate fertilizer and 40% of the potassium fertilizer were applied as the base fertilizer before cabbage transplantation, and the remaining potassium fertilizer, applied as topdressing fertilizer, was added to the soil through the irrigation water (40% of the total amount was used in the early heading, and 20% was used in the late heading stage). The N, P and K fertilizers used were urea (N ≥ 46%), calcium superphosphate (P<sub>2</sub>O<sub>5</sub> ≥ 16%) and potassium sulphate (K<sub>2</sub>O ≥ 50%), respectively.

### 2.3. Measurements

Five cabbage plants with similar growth potential were marked in each plot after transplanting, and their stem diameter, plant height, leaf number, leaf area, leaf spread and leaf area index (LAI) were measured every seven days.

The measurement methods were as follows:

- The measured values of stem diameter were the average values of the marked plants measured by a Vernier caliper (accuracy 0.002 mm) 5 cm from the ground.
- The measured values of plant height, leaf area and leaf spread were obtained from three repeated measurements of the plants with a ruler (accuracy 0.5 mm).
- The leaf number was determined after three repeated counts of the plants.
- The LAI was measured by an LP-80 (AccuPAR PAR/LAI Ceptometer, METER Group, Inc., Pullman, WA, USA) at 11:00 AM and 1:00 PM on a sunny day every 7 days, and the two values per plot were averaged as measured values.

When the cabbage was harvested, the weights of the aboveground part and the head of each cabbage were determined by an electronic scale with a precision of 10 g.

To measure the weight of cabbage roots, three cabbage plants were randomly selected from each plot after harvesting. Pits with a length and width of 40 cm × 40 cm were excavated around their roots, and the depth was divided into three layers: 0–20 cm, 20–40 cm and 40–60 cm. The excavated soil with roots was soaked in barrels for more than 1 hour, after which sieving was conducted and impurities were removed from the roots. The roots were washed with clean water twice and were then returned to the laboratory where remaining water was absorbed with filter paper. After being weighed with an electronic scale with an accuracy of 0.01 g, roots were placed in an oven at 105 °C for 30 min, which was then adjusted to 60 °C to continue drying to a constant weight. In each plot, the aboveground parts of the three plants whose roots had been excavated were divided into stems, leaves and heads; dust on the surface was washed with clear water, followed by wiping with filter paper, and then the aboveground parts were weighed with an electronic scale with an accuracy of 0.01 g. These parts were placed in an oven at 105 °C for 30 min, which was then adjusted to 60 °C to continue drying to a constant weight, after which the aboveground parts were weighed.

The steps used to determine the total nitrogen (TN) content of the cabbage plants were as follows: grinding and sieving the dried root, stem, leaf and head samples separately and sealing them in self-sealing bags to prevent dampness. After the trial, the TN content (%) of these samples was measured by a Kjeldahl nitrogen meter (Kjeltec2300, FOSS, Hillerød, Denmark), and then the TN content of each part of the cabbage plants was calculated; the TN content of each plant part (mg/g) = the TN content (%) of the corresponding part × 10.

A Trime-PICO-IPH sensor was used to measure the soil water content every 2–3 days during the growth period of cabbage (10 cm per layer, 100 cm for the total depth). The evapotranspiration ( $ET_i$ ,  $i = 1, 2, 3$  and 4, representing seeding, rosette, early heading and late heading stages, respectively) of cabbage in each growth stage was calculated by the water balance equation. Total evapotranspiration (ET) was the sum of  $ET_i$  in each growth stage.

Water productivity and N use-related indicators were calculated using the following methods:

- The water productivity of yield ( $WP_Y$ ) is the ratio of crop yield (Y) to ET during the entire crop growth period.
- The water productivity of biomass ( $WP_B$ ) is the ratio of the final biomass (B) to the ET during the entire crop growth period.
- The harvest index (HI) is the ratio of Y to B.
- Total nitrogen uptake ( $TN_U$ ):

$$TN_U = \frac{1}{100} \sum_{i=1}^n N_i B_i \quad (2)$$

where  $n = 4$ ;  $N_i$  is the TN content of roots, stems, leaves and bulbs; and  $B_i$  is the total dry weight of the corresponding part.

- NUE is the ratio of Y to  $TN_U$ .
- The nitrogen harvest index ( $HI_N$ ) is the ratio of fruit nitrogen uptake to  $TN_U$ .

#### 2.4. Experimental Design and Statistical Analysis

Two-season trial on two cabbage (*Brassica oleracea* L. var. *capitata*) cultivars in spring and autumn were carried out for three irrigation and fertilizer coupling treatments. The spring test cabbage cultivar was “Super Chunfeng”, sown on February 8, 2017, transplanted on March 29, and harvested on June 3; the autumn test cultivar was “Zhonggan 201”, sown on July 22, 2017, transplanted on August 25, and harvested on October 28.

The greenhouse was designed with 9 plots (three treatments, each treatment was replicated three times), each of which was 5 m × 2.8 m. To avoid possible lateral exchange of water between plots, a buffer zone between adjacent plots was set, and 500 cm × 60 cm plastic cloth was buried vertically in the middle of the buffer zone. The widths of the protected areas at both ends of the greenhouse were 200 cm and 220 cm. Fertilization by drip irrigation under mulch was used in the trial. The nominal diameter of the insert patch drip irrigation belt was 16 mm, the dripper spacing was 30 cm, the designated flow rate was 1.7–2.0 L/h, and the average measured flow rate was 1.8 L/h. All treatments were planted alternately in wide (60 cm) and narrow rows (40 cm), with a plant spacing of 40 cm. Venturi fertilizer applicators and fertilizer barrels were installed at the head of the irrigation system for topdressing, and the amount of irrigation was measured by a water meter installed at the head. Each plot was equipped with a separate valve in front of it to control the timing of irrigation and fertilization. Trial data were also independently collected in each plot.

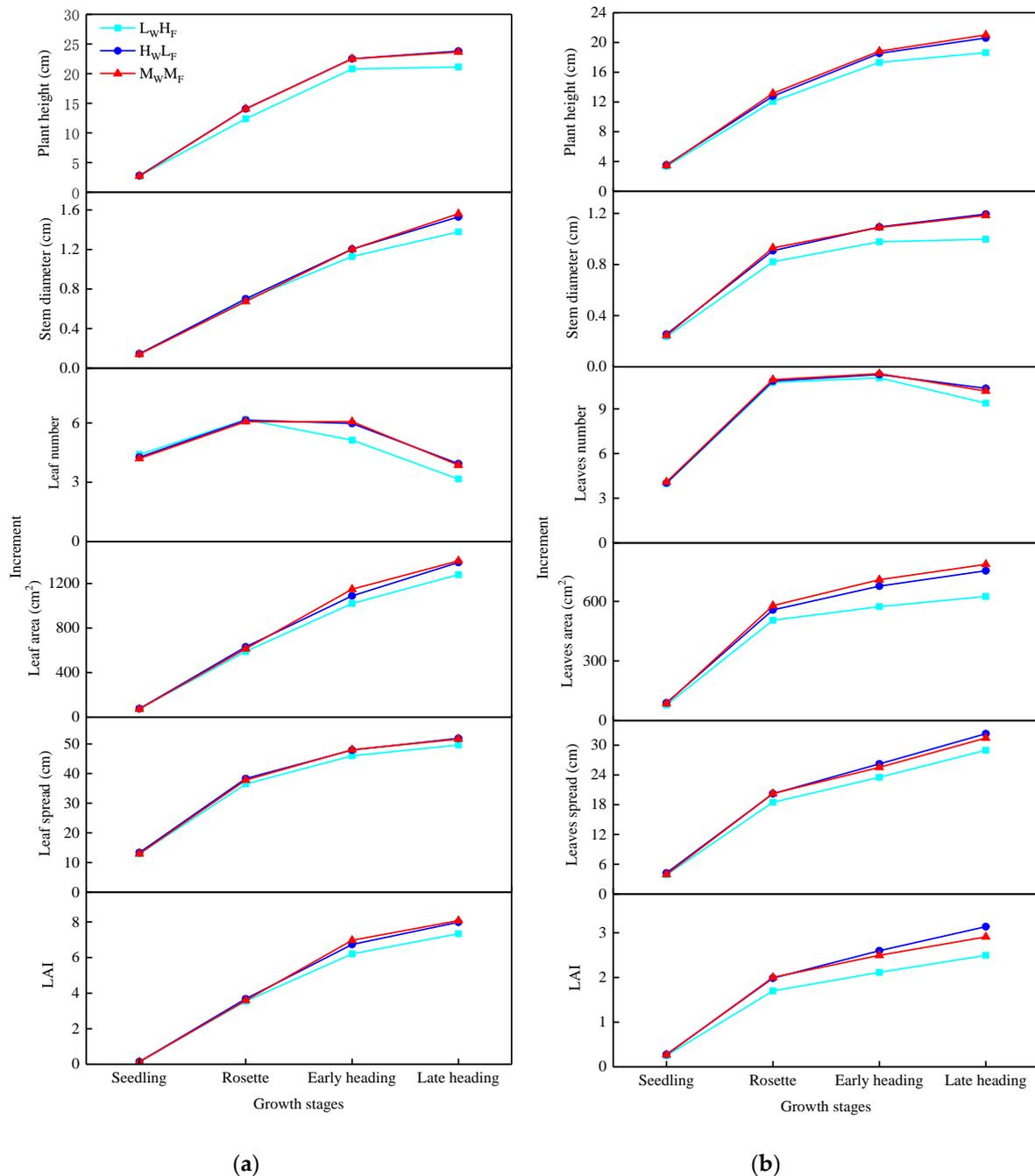
The recording and calculation of the experimental data were carried out in Excel 2016. Origin 8.0 drawing software was used for drawing and analysis. A one-way analysis of variance (ANOVA) was used to analyze the significance of the response of variables to water and fertilizer coupling treatments, and least significance difference (LSD) tests were used for multiple comparisons of mean values of variables. These statistical analyses were performed using the SPSS software package, version 22.0.

### 3. Results and Discussion

#### 3.1. Effects of Different Treatments on the Growth of Cabbage

The increments in the growth indices of cabbage during different growth stages under different water and fertilizer coupling treatments are shown in Figure 3. Because of the different cultivars and growing seasons used in the two trials, the growth indices were also different. Compared with other growth stages, cabbage grew faster in the rosette and early heading stages in spring and in the rosette stage in autumn. The leaf area, leaf spread and LAI of cabbage in autumn were obviously smaller than those in spring. Moreover, different water and fertilizer coupling treatments also had a certain impact on the growth indices during the different stages. The effects of the two-season trial on plant height occurred mainly in the rosette stage and late heading stage, with the following ranking during the rosette stage: treatment 3 ( $M_W M_F$ ) > treatment 2 ( $H_W L_F$ ) > treatment 1 ( $L_W H_F$ ). The stem diameter and leaf area increments of  $L_W H_F$  cabbage in spring were obviously lower than those of the other two treatments from the beginning of the early heading, and these two indices of  $L_W H_F$  in autumn were obviously lower than those of the other two treatments from the beginning of the rosette stage. The leaf number of spring cabbage grew fastest at the seedling stage and began to show negative growth with the gradual senescence of leaves at the beginning of heading. Treatment differences

were mainly observed in the early heading stage, where  $M_W M_F$  was significantly higher than  $L_W H_F$ . The leaf number of autumn cabbage increased fastest in the rosette stage, whereas negative growth occurred in the late heading stage, but there was no significant difference between different treatments in each stage. Different treatments had little effect on the leaf spread of cabbage. The LAI values of spring cabbage at the early heading stage and autumn cabbage at the rosette stage were significantly affected by different treatments, and for both,  $M_W M_F$  was significantly higher than  $L_W H_F$ .



**Figure 3.** Comparison of plant height, stem diameter, leaf number, leaf area, leaf spread and LAI increments of spring cabbage in different stages in response to various treatments (a); comparison of plant height, stem diameter, leaf number, leaf area, leaf spread and LAI increments of autumn cabbage in different stages in response to various treatments (b).

The one-way ANOVA results for the stage increment and cumulative increment of each growth index under different water and fertilizer coupling treatments are shown in Table 4. Among the effects of different treatments on the stage increment of spring cabbage, only the stem diameter reached a significant difference at the late heading stage ( $P < 0.05$ ); the cumulative increment of plant height, stem diameter and LAI reached a significant difference at  $P < 0.05$ , and the leaf number and leaf area reached a significant difference at  $P < 0.01$ . Among the effects on the stage increment of autumn cabbage, plant height at the rosette stage and stem diameter at the late heading stage reached a significant difference at the  $P < 0.05$  level, plant height at the late heading stage reached a significant difference at the  $P < 0.01$  level and the cumulative increment of plant height, stem diameter, leaf area and leaf spread reached a significant difference at the  $P < 0.01$  level.

**Table 4.** One-way ANOVA results for the effects of different water and fertilizer coupling treatments on the stage increments and cumulative increment of plant height, stem diameter, leaf number, leaf area, leaf spread and leaf area index (LAI).

Seasons	Growth Indices	Seedling	Rosette	Early Heading	Late Heading	Accumulated Increment
Spring	Plant height	NS <sup>a</sup>	NS	NS	NS	*
	Stem diameter	NS	NS	NS	*	*
	Leaf number	NS	NS	NS	NS	**
	Leaf area	NS	NS	NS	NS	**
	Leaf spread	NS	NS	NS	NS	NS
	LAI	NS	NS	NS	NS	*
Autumn	Plant height	NS	*	NS	**	**
	Stem diameter	NS	NS	NS	*	**
	Leaf number	NS	NS	NS	NS	NS
	Leaf area	NS	NS	NS	NS	**
	Leaf spread	NS	NS	NS	NS	**
	LAI	NS	NS	NS	NS	NS

<sup>a</sup> Not significant. \* Significant at  $P < 0.05$ . \*\* Significant at  $P < 0.01$ .

According to the above analysis, the effects of different water and fertilizer coupling treatments on the growth indices were mainly manifested in the responses based on the cumulative increment and stage increment for the rosette and late heading stages, and the overall increment of the  $L_W H_F$  indices was less than those of  $H_W L_F$  and  $M_W M_F$ , while the difference between  $H_W L_F$  and  $M_W M_F$  was not significant. Therefore, in the growth period of cabbage, the combination of high irrigation and low N application was more beneficial to increasing the growth indices of cabbage than the combination of low irrigation and high N application.

### 3.2. Effects of Different Treatments on the Biomass Distribution of Cabbage Plants

Cabbage plants were divided into below- and aboveground parts. The belowground part consisted of the roots, and the aboveground part included the stems, leaves and heads. The biomass of each part, the distribution ratio and the total biomass under different water and fertilizer coupling treatments are shown in Table 5. The one-way ANOVA results showed that the effects of different treatments on stem biomass, leaf biomass and total biomass of cabbage in both seasons and root biomass of autumn cabbage were not significant, but the effect on the root biomass of spring cabbage was significant ( $P < 0.05$ ), and its  $M_W M_F$  value was significantly greater than that of  $L_W H_F$ . Different treatments had significant effects on the head biomass; specifically, the head biomass of spring cabbage in  $H_W L_F$  was significantly higher than that in  $M_W M_F$  and  $L_W H_F$ , and the head biomasses of autumn cabbage in  $H_W L_F$  and  $M_W M_F$  were significantly higher than that in  $L_W H_F$ . Gao et al. [35] found that both irrigation and fertilization had significant effects on the root, leaf and total biomass of Chinese cabbage, but the effects of the different water and fertilizer treatments on root, leaf and total biomass were not

significant. Erdem et al. [18] found that irrigation and fertilization had no significant effect on the head biomass of broccoli but had a significant effect on the biomass of leaves.

**Table 5.** Biomass and distribution ratio of each part of cabbage plants under different water and fertilizer coupling treatments.

Seasons	Treatments	Underground Part		Aboveground Parts						Total Biomass (kg/ha)
		Root Biomass (kg/ha)	Ratio <sup>a</sup> (%)	Stem Biomass (kg/ha)	Ratio <sup>a</sup> (%)	Leaf Biomass (kg/ha)	Ratio <sup>a</sup> (%)	Head Biomass (kg/ha)	Ratio <sup>a</sup> (%)	
Spring	L <sub>W</sub> H <sub>F</sub>	522.382b <sup>b</sup>	5.42	467.595ab	4.85	4322.107a	44.84	4327.257b	44.89	9639.341a
	H <sub>W</sub> L <sub>F</sub>	577.270ab	5.59	567.390a	5.50	4562.975a	44.22	4611.722a	44.69	10,319.356a
	M <sub>W</sub> M <sub>F</sub>	617.636a	6.17	446.866b	4.46	4905.675a	49.00	4040.742c	40.36	10,010.920a
	One-way ANOVA	*	-	NS <sup>c</sup>	-	NS	-	**	-	NS
Autumn	L <sub>W</sub> H <sub>F</sub>	200.225a	3.98	175.261a	3.49	1410.242a	28.06	3239.282b	64.46	5025.011a
	H <sub>W</sub> L <sub>F</sub>	218.014a	4.04	184.588a	3.42	1438.512a	26.63	3559.746a	65.91	5400.860a
	M <sub>W</sub> M <sub>F</sub>	221.948a	4.11	171.440a	3.17	1369.224a	25.35	3639.122a	67.37	5401.733a
	One-way ANOVA	NS	-	NS	-	NS	-	*	-	NS

<sup>a</sup> Ratio was the ratio of the average value of root, stem, leaf and head biomass to the average value of the total biomass, respectively. <sup>b</sup> Different letters in the same column show significant differences between different water and fertilizer coupling treatments ( $P < 0.05$ ). <sup>c</sup> Not significant. \* Significant at  $P < 0.05$ . \*\* Significant at  $P < 0.01$ .

Based on the distribution proportion of total biomass in each part, head and leaf biomasses of spring cabbage accounted for the largest proportion, both between 40% and 50%, followed by root biomass between 5.42% and 6.17%, whereas stem biomass accounted for the smallest proportion. The proportion of autumn cabbage head biomass ranged from 64.46% to 67.37%, followed by leaf biomass (25.35% to 28.06%), root biomass (3.98% to 4.11%) and stem biomass (3.17% to 3.49%). Due to the influence of cabbage cultivars, the distribution proportion of total biomass during the two seasons was quite different.

According to the data from the two-season trial, the total biomass and its distribution proportion in each part depended primarily on the cultivar. The total biomass of the spring cultivar was obviously higher than that of the autumn cultivar, but the proportion of head biomass was smaller than that of the autumn cultivar, and the proportion of leaf biomass was larger. This certainly increased the ET and water consumption of crops. The ET results calculated in this trial also confirmed this point. For the same cultivar, the head biomass of H<sub>W</sub>L<sub>F</sub> in spring was 284.47 kg/ha and 570.98 kg/ha higher than that of L<sub>W</sub>H<sub>F</sub> and M<sub>W</sub>M<sub>F</sub>, respectively, while that of M<sub>W</sub>M<sub>F</sub> in autumn was 399.84 kg/ha and 79.38 kg/ha higher than that of L<sub>W</sub>H<sub>F</sub> and H<sub>W</sub>L<sub>F</sub>, respectively. Moreover, the total biomass of L<sub>W</sub>H<sub>F</sub> was obviously lower than that of H<sub>W</sub>L<sub>F</sub> and M<sub>W</sub>M<sub>F</sub>. A comprehensive analysis showed that the effects of H<sub>W</sub>L<sub>F</sub> and M<sub>W</sub>M<sub>F</sub> on the biomass of some parts of cabbage plants were superior to those of L<sub>W</sub>H<sub>F</sub>.

### 3.3. Effects of Different Treatments on the Yield of Cabbage

According to the data in Table 6, from the perspective of yield and yield-related parameters, in the spring trial, the highest market yield of cabbage among the three treatments was observed in response to H<sub>W</sub>L<sub>F</sub>, which was 78.37 t/ha, i.e., 5.00 t/ha and 4.91 t/ha higher than that of L<sub>W</sub>H<sub>F</sub> and M<sub>W</sub>M<sub>F</sub>, respectively. The maximum head weight, minimum head weight and average head weight of H<sub>W</sub>L<sub>F</sub> were also the highest, the maximum head weight and minimum head weight of M<sub>W</sub>M<sub>F</sub> were the lowest, and the yield of L<sub>W</sub>H<sub>F</sub> was the lowest. However, the one-way ANOVA results showed that the effects of the different treatments on the maximum head weight and yield did not reach significant differences, but the minimum head weight reached a significant difference at  $P < 0.05$ , and the average head weight reached a significant difference at  $P < 0.01$ ; for both of them, H<sub>W</sub>L<sub>F</sub> was significantly higher than M<sub>W</sub>M<sub>F</sub> and L<sub>W</sub>H<sub>F</sub>. In addition, based on the coefficient of variation ( $C_v$ ), the discrete degree of yield per plant in H<sub>W</sub>L<sub>F</sub> was the lowest relative to its mean value, compared with M<sub>W</sub>M<sub>F</sub>, the highest. Based on the coefficient of skewness ( $C_s$ ), the yield per plant in H<sub>W</sub>L<sub>F</sub> was the most symmetrical on both sides of its mean value, and the asymmetrical degree of M<sub>W</sub>M<sub>F</sub> was the highest.

**Table 6.** Ratios of maximum, minimum and average head weight,  $C_v$ ,  $C_S$  and yield of cabbage under different water and fertilizer coupling treatments.

Seasons	Treatments	Maximum Head Weight (kg)	Minimum Head Weight (kg)	Average Head Weight (kg)	$C_v$	$C_S$	Yield (kg/ha)
Spring	L <sub>W</sub> H <sub>F</sub>	1.99a <sup>a</sup>	0.71b	1.43b	0.18	−0.42	73,368.25a
	H <sub>W</sub> L <sub>F</sub>	2.05a	0.94a	1.53a	0.14	−0.22	78,371.43a
	M <sub>W</sub> M <sub>F</sub>	1.92a	0.69b	1.43b	0.20	−0.72	73,460.32a
	One-way ANOVA	NS <sup>b</sup>	*	**	-	-	NS
Autumn	L <sub>W</sub> H <sub>F</sub>	1.51b	0.30b	1.07b	0.26	−0.49	55,061.91b
	H <sub>W</sub> L <sub>F</sub>	1.78a	0.52a	1.24a	0.22	−0.18	64,423.81a
	M <sub>W</sub> M <sub>F</sub>	1.66ab	0.51a	1.23a	0.25	−0.70	62,885.71a
	One-way ANOVA	NS	*	**	-	-	**

<sup>a</sup> Different letters in the same column show significant differences between different water and fertilizer coupling treatments ( $P < 0.05$ ). <sup>b</sup> Not significant. \* Significant at  $P < 0.05$ . \*\* Significant at  $P < 0.01$ .

In the autumn trial, from the perspective of yield and yield-related parameters, the highest market yield of cabbage among the three treatments was observed in H<sub>W</sub>L<sub>F</sub>, which was 64.42 t/ha, i.e., 9.36 t/ha and 1.54 t/ha higher than that of L<sub>W</sub>H<sub>F</sub> and M<sub>W</sub>M<sub>F</sub>, respectively. The maximum head weight, minimum head weight and average head weight of H<sub>W</sub>L<sub>F</sub> were also the highest, whereas the lowest values were observed in response to L<sub>W</sub>H<sub>F</sub>. However, the one-way ANOVA results showed that the effect of different treatments on the maximum head weight did not reach a significant difference, but the minimum head weight was significantly affected ( $P < 0.05$ ), and on average, the head weight and yield were significantly affected at  $P < 0.01$ ; for all of them, H<sub>W</sub>L<sub>F</sub> and M<sub>W</sub>M<sub>F</sub> were significantly higher than L<sub>W</sub>H<sub>F</sub>. In addition, the discrete degree of yield per plant in H<sub>W</sub>L<sub>F</sub> was the lowest relative to its mean value, and that of L<sub>W</sub>H<sub>F</sub> was the highest. Compared with L<sub>W</sub>H<sub>F</sub> and M<sub>W</sub>M<sub>F</sub>, H<sub>W</sub>L<sub>F</sub> had the most symmetrical yield distribution on both sides of its mean value, and M<sub>W</sub>M<sub>F</sub> had the greatest degree of asymmetry.

Different water and fertilizer coupling treatments had certain effects on the maximum head weight, minimum head weight, average head weight and yield of cabbage in the two seasons. A comprehensive analysis showed that the yield of the H<sub>W</sub>L<sub>F</sub> treatment was the highest and that of the L<sub>W</sub>H<sub>F</sub> treatment was the lowest. Based on  $C_v$  and  $C_S$ , the yield of the M<sub>W</sub>M<sub>F</sub> treatment was the most discrete and asymmetrical. Therefore, the analysis of the yield data showed that treatment 2 (H<sub>W</sub>L<sub>F</sub>) was better than the other two treatments. Similarly, Gao et al. [35] recommended the application of high water and low fertilizer in the agricultural production of Chinese cabbage.

The yield of cabbage in spring and autumn was the highest in H<sub>W</sub>L<sub>F</sub>, but the yield of cabbage in autumn was significantly lower than that in spring. The reason was not only related to the cultivars but also to the planting season. The temperature of the autumn trial in the heading stage was lower than that of the spring trial, but the relative humidity was higher (Figure 1). Similar results have been obtained in previous research [12,18]. The effect of the water and fertilizer coupling treatments on the yield of cabbage in spring was not significant, but it had a significant effect on the yield of cabbage in autumn. Gao et al. [35] also drew similar conclusions in a study of Chinese cabbage in Northeast China. The different water and fertilizer treatments in the first season had no significant effect on the yield, but the different water and fertilizer treatments in the second season did have a significant effect. Erdem et al. [18] found that different water and fertilizer treatments had no significant effect on broccoli yield in northwestern Turkey.

### 3.4. Effects of Different Treatments on Irrigation Water Productivity of Cabbage

The results of the two-season trial showed that WP<sub>Y</sub> and WP<sub>B</sub> increased with decreasing irrigation. The one-way ANOVA results showed that WP<sub>Y</sub> of spring cabbage and WP<sub>B</sub> of autumn cabbage reached significant differences under different treatments ( $P < 0.05$ ). The effect on WP<sub>B</sub> of spring cabbage

reached a significant difference ( $P < 0.01$ ), while the effect on  $WP_Y$  of autumn cabbage did not reach a significant difference (Table 7). In the spring trial,  $WP_Y$  and  $WP_B$  of  $H_W L_F$  were 13.77% and 13.56% lower than those of  $L_W H_F$ , respectively, and  $WP_Y$  and  $WP_B$  of  $M_W M_F$  were 11.70% and 8.32% lower than those of  $L_W H_F$ , respectively. In the autumn trial,  $WP_Y$  and  $WP_B$  of  $H_W L_F$  were 6.16% and 13.87% lower than those of  $L_W H_F$ , respectively, and  $WP_Y$  and  $WP_B$  of  $M_W M_F$  were 0.76% and 6.54% lower than those of  $L_W H_F$ , respectively. Based on the harvest index (HI), there was no significant difference between the different treatments for the spring experimental results, but the autumn results reached a significant difference at  $P < 0.01$ , and the HI of  $L_W H_F$  was significantly lower than that of  $H_W L_F$  and  $M_W M_F$ .

**Table 7.** Water productivity of yield ( $WP_Y$ ), water productivity of biomass ( $WP_B$ ) and harvest index (HI) of the different water and fertilizer coupling treatments.

Seasons	Treatments	$WP_Y$ ( $kg/m^3$ )	YD <sup>a</sup> (%)	$WP_B$ ( $kg/m^3$ )	BD <sup>b</sup> (%)	HI
Spring	$L_W H_F$	51.55a <sup>c</sup>	0	6.77a	0	7.62a
	$H_W L_F$	44.45b	−13.77	5.85b	−13.56	7.60a
	$M_W M_F$	45.51b	−11.70	6.21b	−8.32	7.34a
	One-way ANOVA	*	-	**	-	NS <sup>d</sup>
Autumn	$L_W H_F$	41.85a	0	3.82a	0	10.97b
	$H_W L_F$	39.27a	−6.16	3.29b	−13.87	11.95a
	$M_W M_F$	41.53a	−0.76	3.57ab	−6.54	11.65a
	One-way ANOVA	NS	-	*	-	**

<sup>a</sup> YD indicates the relative loss based on the water productivity of yield of treatments relative to treatment 1. <sup>b</sup> BD indicates the relative loss based on the water productivity of biomass of treatments relative to treatment 1. <sup>c</sup> Different letters in the same column show significant differences between different water and fertilizer coupling treatments ( $P < 0.05$ ). <sup>d</sup> Not significant. \* Significant at  $P < 0.05$ . \*\* Significant at  $P < 0.01$ .

The  $L_W H_F$  treatment resulted in the highest  $WP_Y$  and  $WP_B$ , but its N application amount was obviously higher than the two other treatments; specifically, its N application amount was twice as high as that of  $H_W L_F$ . Although the  $WP_Y$  and  $WP_B$  values of  $H_W L_F$  in spring were significantly lower than those of  $L_W H_F$ , the HI values were not significantly different among the different treatments; the  $WP_Y$  and  $WP_B$  values of  $H_W L_F$  in autumn were relatively low, but the HI values were the highest. Moreover, the  $WP_Y$ ,  $WP_B$  and HI values of  $M_W M_F$  were not significantly different from those of  $H_W L_F$  in the two-season trial.

The results of this study showed that although high irrigation reduced water productivity, high yields can be achieved, and the irrigation regime developed in this study did not have the problem of excessive use and waste of irrigation water. Erdem et al. [18] reached a similar conclusion in a study of broccoli. Specifically, when the amount of irrigation was  $1.25E_p$  ( $E_p$  is the cumulative pan evaporation measured at a 7-day interval), the yield of broccoli was the highest, but the water productivity was lower than that of the regime with a lower amount of irrigation. In addition, McKeown et al. [24] found that the yield of cabbage increased with increased irrigation during the growth period and concluded that maintaining the soil moisture content near  $\theta_f$  was conducive to obtaining the maximum yield.

### 3.5. Effects of Different Treatments on Nitrogen Uptake and Utilization in Cabbage

#### 3.5.1. Effects of Different Treatments on the Total Nitrogen Content in Each Part of the Plants

The head TN content in the spring trial was close to that of the leaves, which was higher than for the root and stem components. The leaf TN content in the autumn trial was the highest, and the head TN content was close to that of the stem (Table 8). The one-way ANOVA results for the effects of different treatments on the head TN content showed that there was a significant difference in spring cabbage ( $P < 0.05$ ), i.e.,  $M_W M_F$  resulted in a significantly higher value than  $L_W H_F$ , but there was no significant effect for autumn cabbage. The effects of different treatments on the TN content of spring

and autumn cabbage plants reached significant differences at  $P < 0.05$  and  $P < 0.01$ , respectively, and  $M_W M_F$  resulted in a significantly higher value than  $H_W L_F$  and  $L_W H_F$  in spring, while  $M_W M_F$  and  $H_W L_F$  resulted in significantly higher values than  $L_W H_F$  in autumn. Erdem et al. [18] and Gao et al. [35] drew similar conclusions when studying whether applied water and N had significant effects on the TN content of plants.

The results of the two-season trial showed that although  $L_W H_F$  had the highest N application amount, the accumulation of N in each part of the plant was significantly lower than that in  $H_W L_F$  and  $M_W M_F$ . Although  $H_W L_F$  had the lowest N application, the accumulation of N in each part of the plant was not significantly different from that in  $M_W M_F$ . The amount of irrigation per time and the total amount of irrigation during the growth period must have a strong impact on the absorption and utilization of N. Based on the TN content of plants,  $M_W M_F$  and  $H_W L_F$  were better among the three treatments.

### 3.5.2. Effects of Different Treatments on the NUE of Cabbage

The one-way ANOVA results showed that the effects of different treatments on  $TN_U$  and NUE of spring cabbage reached significant differences, and the  $TN_U$  values of  $M_W M_F$  and  $H_W L_F$  were significantly higher than that of  $L_W H_F$ , while the NUEs of  $L_W H_F$  and  $H_W L_F$  were significantly higher than that of  $M_W M_F$ . However, there was no significant difference in the  $TN_U$ , NUE and  $HI_N$  values of autumn cabbage. (Table 9)

**Table 8.** TN content and distribution ratio of cabbage plants under different water and fertilizer coupling treatments.

Seasons	Treatments	Root		Stem		Leaves		Head		Plant	
		TN Content (mg/g)	ND <sup>a</sup> (%)	TN Content (mg/g)	ND (%)						
Spring	L <sub>W</sub> H <sub>F</sub>	26.02 ± 0.56a <sup>b</sup>	0	25.27 ± 0.65b	0	37.01 ± 1.18b	0	36.77 ± 1.64b	0	125.07 ± 3.78b	0
	H <sub>W</sub> L <sub>F</sub>	26.96 ± 0.46a	3.61	23.95 ± 0.12c	-5.22	38.47 ± 0.75ab	3.92	39.51 ± 0.50ab	7.46	128.88 ± 0.75b	3.05
	M <sub>W</sub> M <sub>F</sub>	27.17 ± 2.37a	4.44	28.13 ± 0.58a	11.33	39.35 ± 0.64a	6.32	42.11 ± 1.03a	14.52	136.77 ± 3.09a	9.35
	One-way ANOVA	NS <sup>c</sup>	-	**	-	NS	-	*	-	*	-
Autumn	L <sub>W</sub> H <sub>F</sub>	20.08 ± 0.35a	0	25.09 ± 1.37b	0	38.55 ± 0.75b	0	25.55 ± 0.58a	0	109.27 ± 1.83b	0
	H <sub>W</sub> L <sub>F</sub>	21.75 ± 1.05a	8.31	26.48 ± 0.80ab	5.54	41.43 ± 1.06a	7.47	26.76 ± 0.61a	4.74	116.42 ± 1.65a	6.54
	M <sub>W</sub> M <sub>F</sub>	20.28 ± 0.26a	1.01	28.19 ± 0.66a	12.37	40.69 ± 0.31a	5.54	26.79 ± 0.89a	4.88	115.96 ± 0.62a	6.12
	One-way ANOVA	NS	-	NS	-	*	-	NS	-	**	-

<sup>a</sup> ND indicates the relative increase in the TN content in treatments relative to treatment 1. <sup>b</sup> Different letters in the same column show significant differences between different water and fertilizer coupling treatments ( $P < 0.05$ ). <sup>c</sup> Not significant. \* Significant at  $P < 0.05$ . \*\* Significant at  $P < 0.01$ .

**Table 9.** TN<sub>U</sub>, NUE and HI<sub>N</sub> of cabbage plants under different water and fertilizer coupling treatments.

Seasons	Treatments	TN <sub>U</sub> (kg/ha)	NUE (kg/kg)	HI <sub>N</sub>
Spring	L <sub>W</sub> H <sub>F</sub>	344.27b <sup>a</sup>	213.29a	0.46a
	H <sub>W</sub> L <sub>F</sub>	386.75a	202.64a	0.47a
	M <sub>W</sub> M <sub>F</sub>	392.27a	187.25b	0.43b
	One-way ANOVA	*	*	NS <sup>b</sup>
Autumn	L <sub>W</sub> H <sub>F</sub>	145.72a	378.99a	0.57a
	H <sub>W</sub> L <sub>F</sub>	164.44a	391.83a	0.58a
	M <sub>W</sub> M <sub>F</sub>	162.64a	387.38a	0.60a
	One-way ANOVA	NS	NS	NS

<sup>a</sup> Different letters in the same column show significant differences between different water and fertilizer coupling treatments ( $P < 0.05$ ). <sup>b</sup> Not significant. \* Significant at  $P < 0.05$ .

According to the results of the two-season trial, the increase in the N application amount was not proportional to the plant TN<sub>U</sub>. L<sub>W</sub>H<sub>F</sub> had the highest N application amount, but the plant TN<sub>U</sub> in this treatment was not the highest; on the contrary, it was lower than in other treatments. It can be inferred that a reasonable N application amount should be 200–300 kg/ha when only considering the effect of N applications on the growth of cabbage. On the other hand, the N application amount of H<sub>W</sub>L<sub>F</sub> was 50% of that of L<sub>W</sub>H<sub>F</sub> and 66.7% of that of M<sub>W</sub>M<sub>F</sub>, but the TN<sub>U</sub> value of H<sub>W</sub>L<sub>F</sub> in spring was only 1.41% lower than that of M<sub>W</sub>M<sub>F</sub>, whereas the highest value was observed in response to H<sub>W</sub>L<sub>F</sub> in autumn. This result indicated that increasing the irrigation amount could increase the nutrient uptake of cabbage, thereby increasing the NUE. Therefore, an appropriate water and fertilizer coupling scheme could improve plant TN<sub>U</sub> and NUE. The results showed that the optimal N application amount plus the residual amount of mineralized N in the 0–60 cm soil layer before transplanting cabbage was close to the conclusion of Everaarts and De Moel [23]. In addition, there has been some related research [36–40] showing that the amount of N required for early to mid-season cultivars to obtain the highest yield is 150–308 kg/ha, which was also consistent with the results of the two early season cultivars in this study.

### 3.6. Analysis of the Correlation between ET<sub>i</sub> and Increments in the Indices during the Different Growth Stages of Cabbage

There were significant positive linear correlations between ET<sub>i</sub> and the increments in plant height, leaf area and LAI in each growth stage of cabbage in the two seasons, and the coefficients of determination ( $R^2$ ) were higher than 0.50, while there were weak linear relationships between the evapotranspiration of the late heading (ET<sub>4</sub>) and the increment in stem diameter and leaf number at the late heading stage in the spring trial, and there were weak linear correlations between the evapotranspiration of the seeding (ET<sub>1</sub>) and the increment in leaf spread in the seedling stage in both seasons (Table 10). Therefore, not all increments in the growth indices in the various stages had a significant linear correlation with ET<sub>i</sub>. The main reason is that under certain conditions of light, temperature and humidity, water is not the only factor affecting the growth of cabbage plants, and nutrients, as well as the interaction between water and nutrients, will also have a strong impact on the growth of cabbage plants. However, the relationship between the cumulative increment of the growth indices and ET showed significant quadratic curves ( $R^2 \geq 0.66$ ). It can be seen that increasing the amount of irrigation (i.e., increasing ET) within the range of the irrigation amount designed in this trial was beneficial to the growth of cabbage.

**Table 10.** Regression analysis of ETi and the increments in plant height, stem diameter, leaf number, leaf area, leaf spread and LAI for cabbage during various stages.

Seasons	Growth Stages	Plant height (H)		Stem Diameter (S)		Leaf Number (L)		Leaf Area (A)		Leaf Spread (K)		LAI	
		Regression Equation	R <sup>2</sup>	Regression Equation	R <sup>2</sup>	Regression Equation	R <sup>2</sup>	Regression Equation	R <sup>2</sup>	Regression Equation	R <sup>2</sup>	Regression Equation	R <sup>2</sup>
Spring	Seedling	$H = 0.218ET_1 + 1.559$	0.84	$S = 0.014ET_1 + 0.065$	0.77	$L = 0.606ET_1 + 0.955$	0.79	$A = 10.902ET_1 + 14.755$	0.93	$K = 0.240ET_1 + 11.781$	0.02	$LAI = 0.043ET_1 - 0.092$	0.91
	Rosette	$H = 0.142ET_2 + 1.928$	0.51	$S = 0.001ET_2 + 0.484$	0.78	$L = 0.01ET_2 + 1.258$	0.59	$A = 4.023ET_2 + 287.33$	0.86	$K = 0.120ET_2 + 16.996$	0.61	$LAI = 0.014ET_2 + 2.610$	0.98
	Early heading	$H = 0.004ET_3 + 8.234$	0.98	$S = 0.007ET_3 + 0.148$	0.99	$L = 0.088ET_3 - 4.60$	1.00	$A = 7.210ET_3 + 132.74$	0.69	$K = 0.050ET_3 + 7.414$	0.62	$LAI = 0.055ET_3 + 0.400$	0.93
	Late heading	$H = 0.055ET_4 - 1.581$	0.67	$S = 0.004ET_4 + 0.152$	0.24	$L = -0.001ET_4 - 2.039$	0.001	$A = 3.084ET_4 + 131.97$	0.88	$K = 0.020ET_4 + 2.812$	0.79	$LAI = 0.009ET_4 + 0.752$	0.81
	Whole growth period	$H = -0.0006ET^2 + 0.238ET + 1.260$	0.98	$S = -0.00001ET^2 + 0.011ET + 0.074$	0.99	$L = -0.0003ET^2 + 0.046ET + 4.127$	0.66	$A = -0.014ET^2 + 10.676ET + 3.08$	0.99	$K = -0.001ET^2 + 0.495ET + 10.58$	1.00	$LAI = -0.0001ET^2 + 0.073ET - 0.352$	0.99
Autumn	Seedling	$H = 0.145ET_1 + 1.073$	0.76	$S = 0.014ET_1 + 0.015$	0.64	$L = 0.073ET_1 + 2.841$	0.61	$A = 9.284ET_1 - 68.153$	0.80	$K = 0.227ET_1 + 0.289$	0.37	$LAI = 0.022ET_1 - 0.091$	0.80
	Rosette	$H = 0.07ET_2 + 6.669$	0.52	$S = 0.008ET_2 + 0.346$	0.66	$L = 0.01ET_2 + 6.553$	0.73	$A = 5.092ET_2 + 276.67$	0.60	$K = 0.156ET_2 + 9.949$	0.79	$LAI = 0.029ET_2 + 0.575$	0.86
	Early heading	$H = 0.051ET_3 + 3.357$	0.92	$S = 0.003ET_3 + 0.047$	0.78	$L = 0.014ET_3 - 0.209$	0.96	$A = 5.501ET_3 - 129.71$	0.68	$K = 0.092ET_3 + 1.505$	0.85	$LAI = 0.020ET_3 - 0.327$	0.95
	Late heading	$H = 0.066ET_4 - 1.643$	0.67	$S = 0.007ET_4 - 0.301$	0.84	$L = 0.065ET_4 - 4.731$	0.96	$A = 2.222ET_4 - 51.842$	0.94	$K = 0.054ET_4 + 2.935$	0.94	$LAI = 0.013ET_4 - 0.268$	0.89
	Whole growth period	$H = -0.001ET^2 + 0.304ET - 0.924$	0.99	$S = -0.0001ET^2 + 0.018ET + 0.02$	0.93	$L = -0.001ET^2 + 0.193ET + 1.791$	0.85	$A = -0.05ET^2 + 12.682ET - 73.2$	0.93	$K = -0.001ET^2 + 0.430ET - 1.633$	0.97	$LAI = -0.0002ET^2 + 0.044ET - 0.291$	0.95

#### 4. Conclusions

The growth indices of  $H_W L_F$  and  $M_W M_F$  in the two seasons were larger than that of  $L_W H_F$ ; plant height, stem diameter and leaf area in the two-season trial were significantly different in the different treatments. The yield and biomass of cabbage in spring were higher than those in autumn because of the use of different cultivars and seasons. For the same cultivar, the yields of  $H_W L_F$  in both seasons were the largest, and those of  $L_W H_F$  were the lowest. Different treatments exhibited statistically different of yield in autumn. The head biomass of  $H_W L_F$  in spring was significantly higher than that of the other two treatments, and that of  $H_W L_F$  and  $M_W M_F$  in autumn was significantly higher than that of  $L_W H_F$ . It can be seen that when the total irrigation amount of cabbage was small, the application of higher N amount does not help increase the growth, yield and biomass of cabbage. On the contrary, when the irrigation amount was high, the application of less N was beneficial to increasing the growth and yield of cabbage.

From the perspective of N uptake and utilization, high N application did not increase  $TN_U$  by cabbage plants when the amount of irrigation was low, but increasing the amount of irrigation was conducive to the absorption and utilization of N by crops. Therefore, the design of an appropriate water and fertilizer coupling scheme can improve the N uptake and utilization efficiency of plants. In addition, there was a significant positive linear correlation between  $ET_i$  and the increment in most of the growth indices of cabbage during the various growth stages, which shows that a high irrigation amount is better than a low irrigation amount to promote the growth of cabbage.

As a result, it is recommended that when cabbage is planted in greenhouses in the Beijing–Tianjin–Hebei, the irrigation application of drip irrigation under mulch should be approximately 114.7–125.0 mm and the N fertilization in the  $H_W L_F$  system should be about 200 kg/ha (see Table 3).

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