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Effects of Drip Irrigation with Plastic on Photosynthetic Characteristics and Biomass Distribution of Muskmelon

Jingwei Wang [1,2,*], Wenquan Niu [2,3] and Yuan Li [4]

[1] College of Resources and Environment, Shanxi University of Finance and Economics, Taiyuan, Shanxi 030006, China;
[2] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China; nwq@nwafu.edu.cn (W.N.)
[3] Institute of Soil and Water Conservation, CAS & MWR, Yangling, Shaanxi 712100, China;
[4] Shaanxi Normal University, Xian, Shaanxi 710119, China. liy681@nenu.edu.cn (Y.L.)
* Correspondence: wjwsxufe@163.com (J.W.); Tel: +086 0351 7666149

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Abstract: An experiment was conducted in China to develop guidelines for the mulching drip irrigation of commercial muskmelon crops. Three sets of factors were laid out in rows to give a three × three factorial design. First, plastic covers were placed over the entire growing area (rows and inter-rows, or full), over the rows (half), or no plastic applied (none). Second, there was one irrigation pipe per row (T_1), three pipes for four rows ($T_{3/4}$), or one pipe for two rows ($T_{1/2}$). Finally, the plants were irrigated when the soil water content fell to 60%, 70%, or 80% of field water capacity (FC). Information was collected on net CO_2 assimilation (*Pn*), plant growth, and yield. Overall, maximum *Pn* occurred with half plastic covering, one irrigation pipe for two rows, and irrigation at 80% FC. Plant fresh weight was higher with half plastic covering, one irrigation pipe per row, and irrigation at 70% or 80% FC. Yield was higher with half plastic covering, and irrigation at 70% or 80% FC. There were only small differences in the yield across numbers of irrigation pipes. These results suggest that overall productivity was better with plastic covers over the rows and irrigation at 70% or 80% FC. Differences in productivity with different numbers of irrigation lines per row were small.

Keywords: net CO_2 assimilation; muskmelon; yield; plastic covering mode; lower limit of irrigation; drip irrigation pipe density

1. Introduction

Net CO_2 assimilation (*Pn*) is a determinant for crop growth and biomass accumulation. It is directly affected by temperature, light, and moisture [1], as well as by agronomic measures, such as irrigation [2,3]. Various agronomic measures are taken to regulate crop net CO_2 assimilation and photosynthetic product distribution. For example, crop intercropping makes full use of light energy and increases yield [4]. The improvement of fertilization technology can increase roots' nutrient absorption and leaves' net CO_2 assimilation [5]. Microelement and CO_2 fertilizer can regulate mesophyll cell activity and photosynthate accumulation [6–9]. In arid and semi-arid areas, water shortages are the limiting factor for crop growth. Drip irrigation with a plastic covering (DIP) is widely used due to its high-efficiency water savings. DIP involves factors such as irrigation volume, the plastic covering mode, and drip irrigation pipe density. Different combinations of these factors will cause differences in soil moisture, temperature, and enzymes [10]. These combinations may affect a crop's photosynthetic characteristics, biomass accumulation, and yield. Previous studies have found that crop yield is mainly affected by irrigation volume [11]. The water deficit stress caused by inadequate drip irrigation reduces the crop leaves' net CO_2 assimilation rate (*Pn*), transpiration rate (*Tr*), and stomatal conductance (*Gs*) [12], but it can optimize photosynthate distribution and increase yield [13]. Other studies indicate that different plastic covering methods can regulate soil moisture and temperature environment and improve crop *Pn*, *Gs*, and yield [14,15]. In addition, drip irrigation pipe density can significantly affect the spatial heterogeneity of soil moisture and temperature and the activity of soil enzymes in the crop root-zone; these changes indirectly affect the distribution of crop photosynthetic products [16]. Some studies have reported that plastic-mulching and irrigation management changed soil urease activity [17] and that soil urease regulated nitrogen cycling and increased crop yields [18]. Therefore, different combinations of irrigation volume, plastic covering mode, and drip irrigation pipe density could regulate crop photosynthetic characteristics, both theoretically and practically, thereby affecting photosynthetic product distribution and yield. Some researchers have increased crop *Pn* and yield through different combinations of irrigation volume and plastic covering modes [3,19]. However, it is not clear how different combinations of irrigation volume, plastic covering modes, and drip irrigation pipe densities can regulate a crop's photosynthetic characteristics and yield. Is it possible to further improve the photosynthetic efficiency and yield of crops by optimizing the combined parameters of their different irrigation volumes, plastic covering modes, and drip irrigation pipe densities? This is a very interesting question and worthy of further study to enhance the productivity potential of DIF measures.

Muskmelon is a healthy fruit rich in nutrients with and a unique taste. It has a large market demand and high economic benefits. China has become the largest producer of melon in the world [20]. However, there are problems with the cultivation of this fruit, such as the necessary large water and fertilizer input, soil nitrogen accumulation [21], and low photosynthetic efficiency [22]. DIF is a common method for muskmelon cultivation. The effects of mulching methods and irrigation rates on muskmelon growth have been studied by many researchers [23,24]. However, the effect of drip irrigation pipe density has received little attention. In addition, the regulation mechanism of DIF on muskmelon's photosynthetic characteristics and biomass distribution is not clear. This study uses an orthogonal design to evaluate the effects of different combinations of irrigation volume, plastic covering modes, and drip irrigation pipe densities on muskmelon leaves' photosynthetic parameters, biomass accumulation, and distribution in an attempt to further exploit the potential of DIF and regulate muskmelon photosynthetic product distribution and yield.

2. Materials and Methods

2.1. Experimental Design

The experiment was carried out in a greenhouse (108 m long and 8 m wide) in Yangling Agricultural High-Tech Zone (34° 16' N, 108° 08' E), Shaanxi Province, China, from October 2014 to May 2015. The soil's bulk density was 1.35 $g\cdot cm^{-3}$, and the soil field's water capacity was 31.54%. The climate in this area is semi-arid, the average annual sunshine is about 2164 h, and the frost-free period is about 210 d. The experiment included three factors: the plastic covering method (P), the drip irrigation pipe density (T), and the lower limit of irrigation (L). Each factor had three levels. There were nine treatments and three repetitions for each treatment, with a total of 27 plots. The experiment was based on an orthogonal design table L9 (3^4), as in Table S1. The specific experimental design is shown in Table 1.

Table 1. Experimental factors and design.

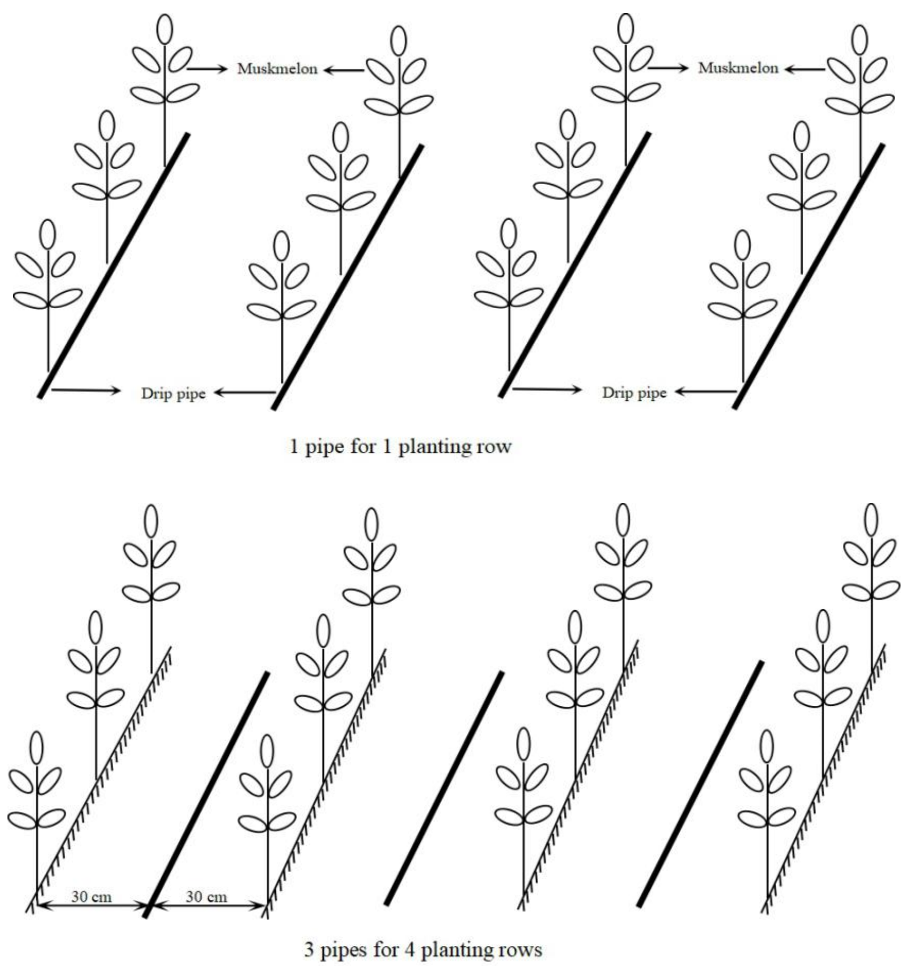
Factors	Levels	Experimental setting	Materials
Plastic covering method	Full plastic covering (F)	Both rows and inter-row were covered.	White high-pressure low-density polyethylene plastic, with 0.014 mm thick.
	Half plastic covering (H)	Rows were covered.	
	No plastic covering (N)	No rows and inter-row were covered.	
Drip irrigation pipe density (Figure 1)	1 pipe per 1row (T_1)	One pipe was laid for each row.	The embedded inner inlay flat drip irrigation pipes, with 16 mm diameter, 0.3 mm wall thickness, 30 cm emitter distance, 0.1 Mpa working pressure, and 1.2 $L \cdot h^{-1}$ flow.
	3 pipes for 4 rows ($T_{3/4}$)	Three pipes were laid in three spaces between four rows of a group.	
	1 pipe for 2 rows ($T_{1/2}$)	One pipe was laid between two prows.	
Lower limit of irrigation	60% field water capacity (F) (L_{60})	The upper limit was 70% F.	Irrigation water was derived from local agricultural water.
	70% field water capacity (L_{70})	The upper limit was 80% F.	
	80% field water capacity (L_{80})	The upper limit was 90% F.	

The muskmelon cultivar "Shantian No. 1" was sown in seedling plugs, and its seedlings of 20 d were transplanted in double rows with a row spacing of 0.6 m. The planting plot was 6.0 m long and 1.0 m wide with double ridges. The cross-section of each planting plot was an inverted trapezoid, with an upper bottom width of 0.8 m, a lower bottom width of 0.4 m, and a depth of 0.2 m. The base fertilizer, consisting of 90 kg·ha^{-1} ternary compound fertilizer ($N/P_2O_5/K_2O$ = 15:15:15) and 160 kg·ha^{-1} organic fertilizer, was applied once before planting.

When muskmelon seedlings were transplanted, the irrigation volume was the same in each plot. The water management (L_{60}, L_{70}, and L_{80}) began after 13 days of transplanting. The information on the actual irrigation amount is provided in Table S2. During the experiment, three 1.0 m probes (Field TDR 200; Spectrum, USA) were installed in each planting plot to monitor the soil moisture at intervals of 10 cm, and the monitoring value was corrected by the drilling and drying gravimetric method. Water replenishment was calculated according to the following formula [16]:

$$M = s\rho_b ph\theta_f\left(q_1 - q_2\right) / \eta \quad (1)$$

where M is the irrigation amount, m^3; *s* is the wet area in the soil, m^2; ρ_b is the bulk density of the soil, 1.35 g·cm^{-3}; *p* is the wetting ratio; *h* is the wetting depth of the soil, 40 cm; θ_f is the maximum field water capacity, 31.54%; q_1 and q_2 are the upper limits of irrigation and the measured soil moisture, %*F*; and η is the water use coefficient, 0.95.



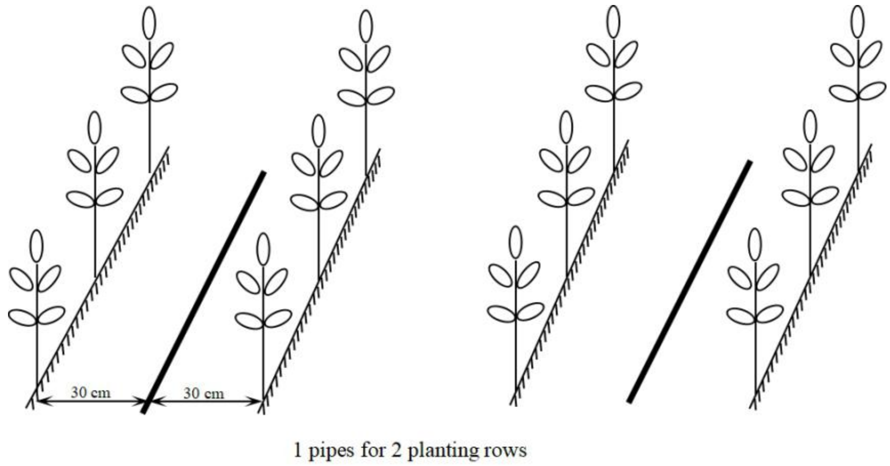


Figure 1. Diagram of drip irrigation pipe density.

2.2. Measured Indicators

2.2.1. Leaf Photosynthetic Characteristics

The photosynthetic characteristics were measured using an LI-6400 portable photosynthetic system (LI-COR, Lincoln, Nebraska, NE, USA) during the flowering period (FP), fruit swelling period (FSP), and mature period (MP). In each measurement activity, three plants of uniform growth were selected for each treatment, and three leaves were selected for each plant with sufficient light exposure and a relatively consistent leaf position. The determination time was selected as the morning of a clear day with few clouds for each growth period from 9:00 to 11:00 a.m. Specific measurement indicators included leaves *Pn*, *Tr*, *Gs*, and *Ci*. Each leaf was measured three times, and the mean value was calculated. The system contained a built-in light source and an open-air path, and the illumination was set to 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

2.2.2. Biomass, Yield, and Total Nitrogen Contents

Before the muskmelon fruits were harvested, three evenly grown plants were selected per treatment. The fruits were harvested separately for each treatment, and the yield ($t \cdot hm^{-2}$) was calculated. The above-ground plants were reaped and collected. The underground roots were collected using the excavation method, with a 60 × 50 × 50 cm rectangular body formed by the centerlines of the adjacent plants. The root samples were separated from the soil and packed into mesh bags and then brought back to the laboratory for cleaning and measuring. The rhizosphere soil samples were placed in sterile plastic tubes and taken to the laboratory for measuring. The plant and root samples were weighed by a 0.01-g electronic balance.

The nitrogen analysis was performed after the fruits were received. The plant and fruit samples were dried in a forced-air oven (fixed at 105 °C for 30 min and dried to a constant weight at 75 °C). The total nitrogen contents of the plant, root, and fruit were determined using the semi-micro Kjeldahl method.

2.2.3. Soil Urease Activity

The soil samples in FP, FSP, and MP were collected using the method, as shown in Section 2.2.2. Soil urease activity (mg NH_3-$N \cdot g^{-1} \cdot d^{-1}$) was measured using the phenol-sodium hypochlorite colorimetric method [17].

2.3. Data Processing

The mean errors, one-way variance (one-way), and two-factor interactive analysis of the measured indicators were performed using SPSS 22.0 (IBM, Armonk, NY, USA). Tables and figures were developed using Excel 2010. The structural equation model analysis was performed using AMOS 25.0 (IBM, Armonk, NY, USA).

3. Results

3.1. Net CO_2 Assimilation Rate (P_n)

P_n was significantly affected by the plastic covering method and drip irrigation pipe density ($p < 0.05$; Table 2). The half plastic covering (H) increased P_n by 29.54%, 9.52%, and 11.80%, respectively, in FP, FSP, and MP compared to the full plastic covering (F). Similarly, H increased Pn by 25.32% and 10.26%, respectively, in FP and FSP compared to the no plastic covering (N) group. Using one pipe for two rows ($T_{1/2}$) increased the P_n in FSP by 20.24% and 27.58% compared to using one pipe for two rows (T_1) and three pipes for four rows ($T_{3/4}$), respectively. However, the P_n of $T_{1/2}$ in MP showed an increase of 11.85% compared to $T_{3/4}$. $T_{3/4}$ increased P_n in FSP by 12.62% compared to T_1. However, the lower limit of irrigation only had a significant effect on P_n in FSP. An 80% field capacity (L_{80}) increased the P_n in FSP by 43.62% and 11.36% compared to the results for 60% field capacity (L_{60}) and 70% field capacity (L_{70}), respectively. Therefore, the results of the single factor analysis showed that the optimal factors were H and $T_{1/2}$. Overall, the optimal combination of H, $T_{1/2}$, and L_{80} can improve P_n.

Table 2. Effect of plastic covering method, drip irrigation pipe density, and lower limit of irrigation on net CO_2 assimilation rate (P_n) (μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$).

Growth periods	Single experimental factors			
Flowering period (FP)	P*	F: 13.37b	H: 17.32a	N: 13.82b
	T*	T_1: 14.03b	$T_{3/4}$: 15.80a	$T_{1/2}$: 14.68ab
	L^{ns}	L_{60}: 14.50a	L_{70}: 14.79a	L_{80}: 15.23a
Fruit swelling period (FSP)	P*	F: 19.53b	H: 21.39a	N: 19.40b
	T*	T_1: 19.12b	$T_{3/4}$: 18.02c	$T_{1/2}$: 22.99a
	L*	L_{60}: 16.00c	L_{70}: 20.78b	L_{80}: 23.14a
Mature period (MP)	P*	F: 21.35b	H: 23.87a	N: 23.42a
	T*	T_1: 24.41a	$T_{3/4}$: 21.09b	$T_{1/2}$: 23.59a
	L^{ns}	L_{60}: 22.77a	L_{70}: 23.01a	L_{80}: 22.98a

Note: P is plastic covering method (full, half, and no plastic plastic covering, i.e., F, H, and N); T is drip irrigation pipe density (one pipe per one row (T_1), three pipes for four rows ($T_{3/4}$), and one pipe for two rows ($T_{1/2}$)); L is and lower limit of irrigation (60%, 70%, and 80% field capacity, i.e., L_{60}, L_{70}, and L_{80}). *and ns show significant ($p < 0.05$) and not significant difference of experimental factors, respectively. The different lowercase letters show significant difference ($p < 0.05$) in different level of the same factor. The following is the same.

3.2. Stomatal Conductance (G_s)

The G_s in FSP was significantly affected by the applied plastic covering method ($p < 0.05$; Table 3). H increased G_s in FSP by 14.81% and 6.89% compared to F and N, respectively, whereas N promoted G_s in FSP by 7.40% compared to F. The G_s of the three periods was significantly affected by different levels of drip irrigation pipe density and the lower limit of irrigation. Specifically, the magnitudes of these effects were expressed as $T_{1/2} > T_{3/4} > T_1$ and $L_{60} = L_{80} > L_{70}$ in FP, $T_1 > T_{1/2} > T_{3/4}$ and $L_{70} > L_{80} > L_{60}$ in FSP, and $T_{3/4} > T_{1/2} > T_1$ and $L_{80} > L_{60} = L_{70}$ in MP. After a comprehensive analysis, H,

$T_{1/2}$, and L_{80} were shown to form the best combination for increasing G_s, while the second-place combination was H, $T_{3/4}$, and L_{80}.

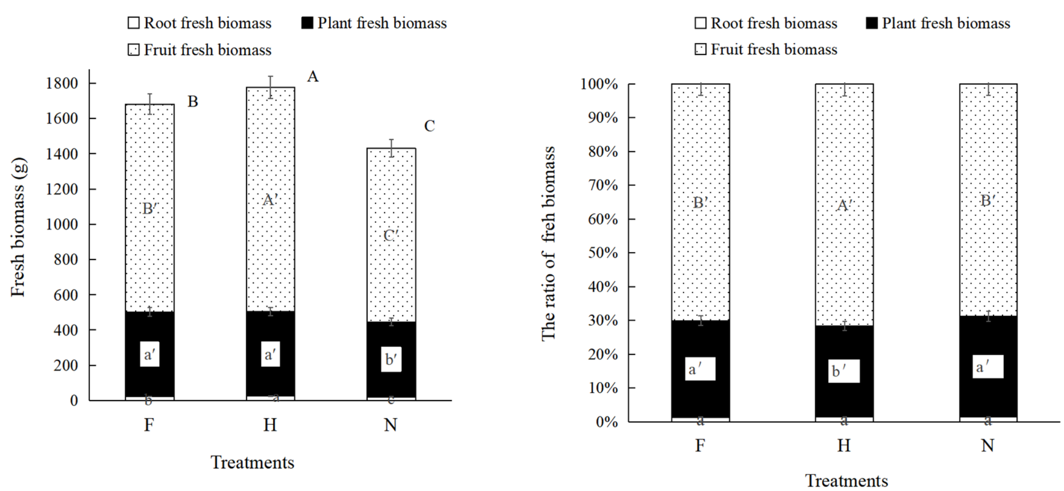
Table 3. Effect of plastic covering method, drip irrigation pipe density, and lower limit of irrigation on stomatal conductance (G_s) (mmol·m^{-2}·s^{-1}).

Growth periods	**Single experimental factors**			
Flowering period (FP)	P^{ns}	F: 0.21a	H: 0.23a	N: 0.22a
	T*	T_1: 0.17c	$T_{3/4}$: 0.22b	$T_{1/2}$: 0.26a
	L*	L_{60}: 0.23a	L_{70}: 0.19b	L_{80}: 0.23a
Fruit swelling period (FSP)	P*	F: 0.27c	H: 0.31a	N: 0.29b
	T*	T_1: 0.30a	$T_{3/4}$: 0.26c	$T_{1/2}$: 0.29b
	L*	L_{60}: 0.26c	L_{70}: 0.37a	L_{80}: 0.28b
Mature period (MP)	P^{ns}	F: 0.40a	H: 0.38a	N: 0.41a
	T*	T_1: 0.37c	$T_{3/4}$: 0.43a	$T_{1/2}$: 0.40b
	L*	L_{60}: 0.39b	L_{70}: 0.38b	L_{80}: 0.42a

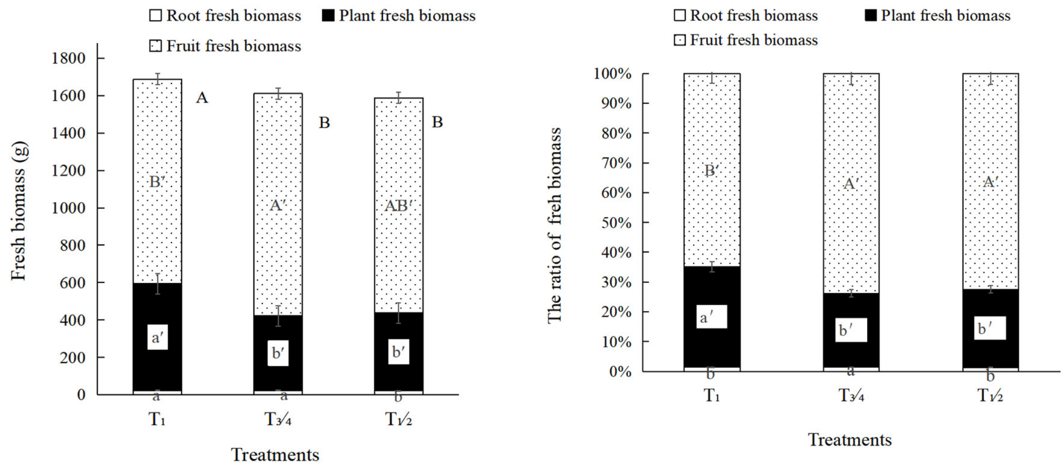
3.3. Muskmelon Biomass

Compared with F and N, H increased fruit fresh biomass by 7.98% and 29.24%, plant fresh biomass by 10.83% and 22.77%, and total fresh biomass by 5.65% and 24.15%. $T_{1/2}$ and $T_{3/4}$, respectively, increased fruit fresh biomass by 8.59% and 5.05% compared to that of T_1. L_{70} and L_{80}, respectively, increased fruit fresh biomass by 18.42% and 16.46% compared to that of L_{60} and, respectively, increased the total fresh biomass by 14.79% and 15.97% compared to that of L_{60}.

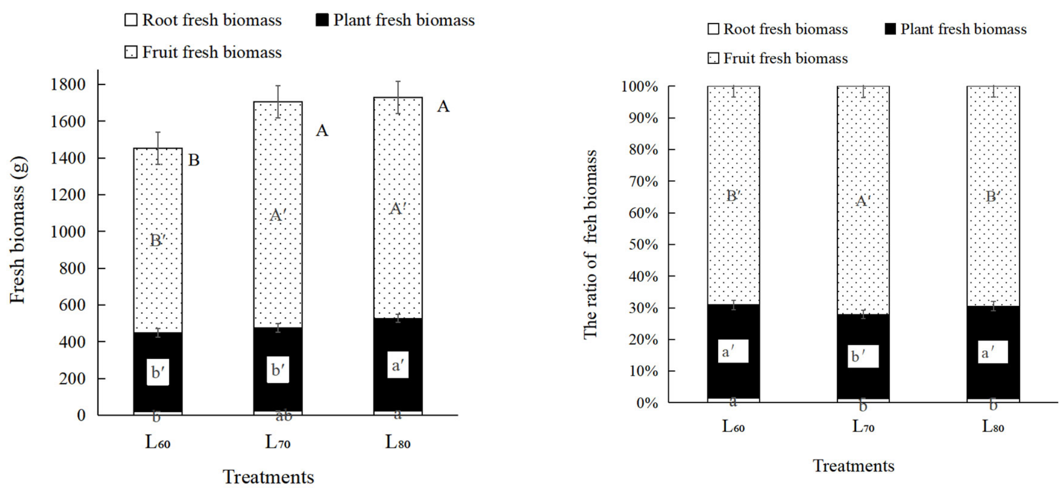
The fresh biomass distribution was significantly affected by experimental factors (Figure 2). Compared with F and N, H reduced the proportion of plant fresh biomass to the total biomass by 5.64% and 9.44%, respectively, but increased the fruit fresh biomass proportion by 2.20% and 4.10%, respectively. $T_{1/2}$ and $T_{3/4}$ decreased the plant fresh biomass proportion by 36.71% and 28.83%, respectively, compared to T_1; however, they increased the fruit fresh biomass proportion by 12.16% and 10.48%, respectively. L_{70} decreased the plant fresh biomass proportion by 9.88% and 9.05% compared to that of L_{60} and L_{80}, respectively. In addition, L_{70} increased the fruit fresh biomass proportion by 4.44% and 3.83% compared to that of L_{60} and L_{80}, respectively. Therefore, H, $T_{1/2}$, and L_{70} significantly increased the fruit fresh biomass proportion.



(a) Plastic covering method.



(b) Drip irrigation pipe density.



(c) Lower limit of irrigation.

Figure 2. Fresh biomass accumulation and distribution by the plastic covering method, drip irrigation pipe density, and lower limit of irrigation. **Note:** F, H, and N are full, half, and no plastic covering, respectively. T_1, $T_{3/4}$, and $T_{1/2}$ are one pipe per one row, three pipes for four rows, and one pipe for two rows, respectively. L_{60}, L_{70}, and L_{80} are 60%, 70%, and 80% field water capacity, respectively. a (b,c), a′ (b′,c′), A′ (B′,C′) and A (B, C) mean the significant difference ($p < 0.05$) of root, plant, fruit fresh and total biomass of different treatments, respectively.

3.4. Simple Correlation Analysis and Structural Equation Model

The correlations of the photosynthetic characteristic parameters, root fresh biomass, plant fresh biomass, and fruit fresh biomass during the three growth periods were analyzed (Table 4). It was found that fruit fresh biomass was positively correlated with the root fresh biomass, total fresh biomass, and P_n in FP. The root fresh biomass had a positive correlation with the total fresh biomass and P_n in FP. A structural equation analysis of the effect of P_n on fruit fresh biomass was also performed (Figure 3). The results showed that the total effects of P_n in FP, FSP, and MP on fruit fresh biomass were 0.55, 0.09, and −0.05, respectively. The root fresh biomass had a total effect of 0.58 on the fruit fresh biomass. The variables in this model can account for 89% of the variation in the fruit fresh biomass of muskmelon.

Table 4. Simple correlation analysis of biomass and *Pn.*

	Fruit fresh biomass	Plant fresh biomass	Root fresh biomass	Total fresh biomass	P_n in FP	P_n in FSP	P_n in MP	C_i in MP
Fruit fresh biomass	1.00	0.20	0.78*	0.87**	0.75*	0.55	−0.03	0.00
Plant fresh biomass		1.00	0.43	0.63	−0.18	0.25	0.33	−0.10
Root fresh biomass			1.00	0.87**	0.73*	0.25	0.03	−0.17
Total fresh biomass				1.00	0.57	0.55	0.25	−0.13
P_n in FP					1.00	0.32	0.02	−0.17
P_n in FSP						1.00	0.32	0.40
P_n in MP							1.00	−0.55

Note: * stands for significant correlation, and ** stands for extremely significant correlation. *Pn* is net CO_2 assimilation rate. FP, FSP, and MP mean flowering period, fruit swelling period, and mature period, respectively.

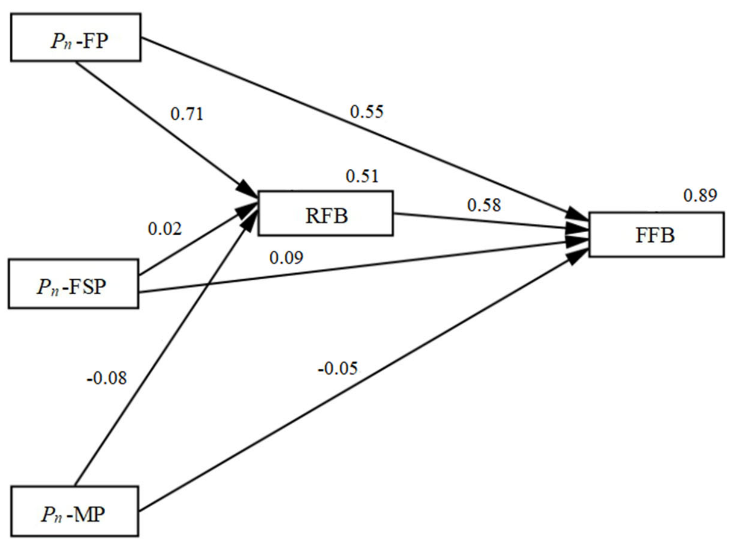


Figure 3. Structural equation model of the effect of *Pn* on melon fruit fresh biomass. **Note:** *Pn*-FP, *Pn*-FSP, and *Pn*-MP mean net CO_2 assimilation rate (*Pn*) in flowering period, fruit swelling period, and mature period, respectively. RFB and FFB are root and fruit fresh biomass, respectively.

3.5. Soil Urease Activity

The soil urease activity under three drip irrigation pipe densities showed a significant difference in each period (Figure 4). In FP, $T_{1/2}$, and $T_{3/4}$ increased soil urease activity by 34.71% and 35.28% compared to T_1, respectively. In FSP, the soil urease activity of $T_{1/2}$ was not significantly different from that of $T_{3/4}$ and T_1. However, T_1 increased soil urease activity by 32.93% compared to $T_{3/4}$. In MP, $T_{1/2}$ and $T_{3/4}$ increased soil urease activity by 22.26% and 56.90% compared to T_1, respectively.

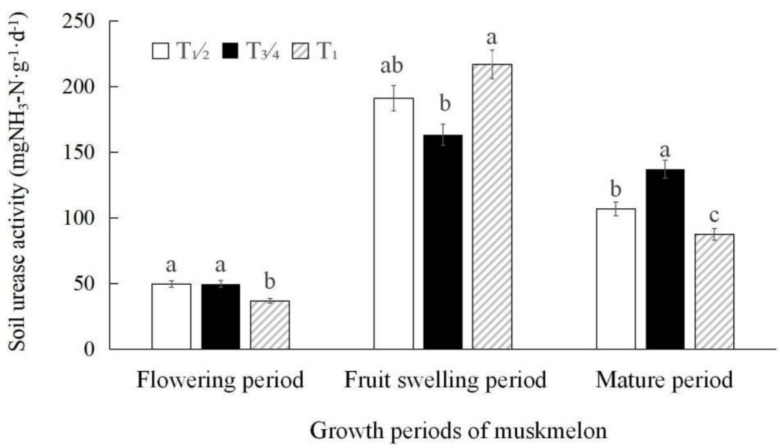


Figure 4. Effect of drip irrigation pipe density on soil urease activity. **Note:** Lowercase letters mean that soil urease activities were significantly different ($p < 0.05$) for different drip irrigation pipe densities in the same period.

4. Discussion

4.1. Half Plastic Covering was Beneficial to Pn and Fresh Biomass

In this study, the half plastic covering was able to keep *Pn* at a high level during the whole growth period (Table 2), but it enhanced *Gs* (Table S3) and decreased *Ci* (Table S3) in the fruit swelling period, compared to the other two covering methods. This is different from the findings that a semi-mulch covering can significantly improve *Ci,* possibly due to the adoption of a straw covering [25]. Many studies have observed that a decrease of *Pn* is determined by the non-stomatal limitations when *Pn* and *Gs* decrease with a decrease of *Ci* [26]. However, there are few clear studies that explain why *Pn* and *Gs* increase with a decrease of *Ci*. The increase in the photosynthetic activity of mesophyll cells may enhance CO_2 consumption, resulting in an increase of *Pn* and decrease of *Ci* [27]. The half plastic covering might have enhanced the photosynthetic activity of mesophyll cells and increased *Pn*, which consumed more leaf intercellular CO_2 and then correspondingly reduced *Ci*. The decrease of *Ci* promoted the opening of the leaves' stoma and increased *Gs*, whereas the increased *Gs* enhanced the absorption of more CO_2 by the leaves and improved *Pn*. A previous study found that the *Pn* and *Gs* of soybean increased with a decrease of *Ci*, which is similar to the results of our study. However, their study added exogenous silicon into the soil, and this was able to enhance the light capturing ability of leaves and improve *Pn* [28].

In addition, the half plastic covering can significantly promote root–soil–microorganism interactions and enhance the nutrient uptake by plant roots [29], which will indirectly affect and improve *Pn.* In this study, it was found that the half plastic covering increased the total fresh biomass by 5.65% and 24.15%, respectively, compared with the full covering and no plastic covering. The increase in total fresh biomass was due to *Pn* improvement. On the contrary, the vigorous photosynthetic product output also stimulates the enhancement of *Pn*. Our previous studies have found that a half plastic covering can maintain the soil and air connection and avoid anaerobic factors from increasing in the soil. In addition, there was no difference in the soil temperature between half the plastic covering and the full plastic covering. At the same time, the half plastic covering also created a more uniform distribution of 0–60 cm soil moisture in the root-zone, resulting in better soil moisture and temperature environment [30]. This may be the internal mechanism in soil by which a half plastic covering ultimately improves *Pn*, but the related changes in the photosynthetic physiological characteristics of leaves need to be studied further.

4.2. The Smaller Drip Irrigation Pipe Density was Beneficial to Pn

Previous studies have shown that drip irrigation pipe density significantly affects soil moisture, temperature, and permeability [31,32]. A smaller drip irrigation pipe density could produce a more uniform distribution of soil moisture and temperature around the root system and create better soil permeability, which would improve the soil's enzymatic activity [33]. In this study, one pipe for two rows was conducive to maintaining higher soil urease activity during the muskmelon growth period (Figure 4). High activity of soil urease can promote the conversion and absorption of soil nitrogen and affect a plant's net CO_2 assimilation [34]. Our determination also found that one pipe for two rows increased the nitrogen content in muskmelon plant stems by 10.31% and 2.26% compared to one pipe for one row and three pipes for four rows, respectively (Table S4). This may be the real reason why a smaller drip irrigation pipe density (one pipe for two rows) significantly improved *Pn*. A previous study of our research group also found that an uneven soil moisture distribution was created by a larger drip irrigation pipe density (one pipe for one row) [34]. The water supply method of one pipe for one row was able to more easily deliver soil moisture to the root system and led to greater moisture in the local soil of the root area. These changes might be more beneficial to the soil moisture exchange in the continuous system of "soil–plant–atmosphere". Therefore, using one pipe for one row increased the T_r of leaves. However, using one pipe for one row also decreased the soil's urease activity in the flowering period, while that in the mature period was relatively higher. Overall, this would not be conducive to the improvement of plant nitrogen absorption and photosynthetic rate [35]. The effect of using three pipes and four rows on soil urease activity was similar to that when using one pipe and two rows. In addition, the greater uniformity of soil moisture distribution did not lead to high moisture content in the local soil around the roots but might delay the moisture exchange rate in the "soil–plant–atmosphere" continuous system, resulting in a plant *Tr* lower than that when using one pipe for one row and one pipe for two rows.

4.3. Lower Limit of Irrigation Significantly Affected Pn during Fruit Swelling Period

Plants regulate CO_2 absorption by adjusting the *Gs* of leaves during the photosynthetic process [36]. A value of 80%*F* could maintain a high level of *Gs*, which is conducive to CO_2 absorption and *Pn* improvement. However, 80%*F* resulted in the highest *Pn* and the lowest *Ci* during the fruit swelling period. The increased *Pn* of the mesophyll cells consumed more intercellular CO_2, resulting in a lower value of *Ci* [28]. In this study, the three lower limits of irrigation had no significant difference on *Pn* in the flowering and mature period but had a significant effect on *Pn* during the fruit swelling period. Because the fruit swelling period is a key period for the synthesis of muskmelon photosynthetic products and because plants need considerable water to grow, larger drought stresses under 60%*F* caused the plants to close more stomata of their leaves, which reduced transpiration [37]. The measured values also showed that the *Gs* and the *Tr* of 60%*F* were the smallest during the fruit swelling period, yielding the lowest value of *Pn* for 60%*F*. However, the *Ci* value of 60%*F* was higher than that of 70%*F* and 80%*F* due to the slow intercellular CO_2 consumption resulting from the minimum *Pn* of 60%*F.* The moderate drought stresses created by 70%*F* might fundamentally meet the water demand of the muskmelon in the fruit swelling period. This might mean that 70%*F* also had larger *Gs* and *Tr* values, with only the secondary *Pn* at 80%*F.* In addition, a medium level *Pn* of 70%*F* might cause its intercellular CO_2 consumption rate to be higher than that of 60%*F* but lower than that of 80%*F*, resulting in a medium level of *Ci*.

A study found that the muskmelon *Pn* was the highest in the early growth period when the soil moisture was 60% to 80%*F* [38]. This finding is similar to the results of this study. However, this finding came from a pot-based experiment; there is currently no study on the *Gs* and the whole growth period of melon. Another study showed that a larger lower limit of irrigation significantly improved the *Pn*, *Gs,* and *Tr* of melon in the partial growth period, which is consistent with the results of this study. However, the photosynthetic characteristics of melon leaves during the whole growth period were not monitored [39].

4.4. Determination of the Combination of Different Mulching Drip Irrigation Measures

Biomass accumulation and yield improvement are the basic purposes of agricultural production. In this study, the root fresh biomass and *Pn* in FP and FSP promoted fruit fresh biomass (Figure 3). The muskmelon yield was positively correlated with the fruit fresh biomass, root fresh biomass, and total biomass (Table S5). The half plastic covering was found to promote the stem diameter of muskmelon plants, which was able to accelerate the nutrient exchanges between roots and plants and increase photosynthetic product accumulation [40]. Therefore, the half plastic covering significantly increased the muskmelon's fresh biomass and yield (Figure S1), in addition to keeping *Pn* at a high level. The medium and low drip irrigation pipe density (one pipe for two rows and three pipes for four rows) was able to help distribute more photosynthetic products into fruits (Figure 2) and to increase yield (Figure S1). Moderate drought stress (70%*F*) enhanced yield as a result of the proportion of the fruits' fresh biomass increase. There was no significant difference in the muskmelon yield between low drought stress (80%*F*) and 70%*F,* even though 80%*F* promoted a greater distribution of photosynthetic products to the plants. The reason for this result may be that the relatively sufficient water supply (80%*F*) was able to reduce the heat dissipation ratio of the light energy absorbed by the leaves, increase the energy conversion ratio in the optical system [41], and improve the photosynthetic products and yields. However, a relatively scarce water supply (60%*F*) had the opposite effect on the absorption and utilization of light energy by leaves, as the yield was relatively reduced. Therefore, the optimal combination of a half plastic covering and one pipe for two rows and the sub-optimal combination of a half plastic covering and three pipes for four rows should be considered. The lower limit of irrigation should be 70%*F.*

5. Conclusion

The photosynthetic characteristics, biomass accumulation, and distribution of muskmelon were significantly affected by the plastic covering method, drip irrigation pipe density, and lower limit of irrigation. The half plastic covering maintained the *Pn* and *Gs* at a high level during the whole growth period and increased fruit biomass and yield. One pipe for two rows promoted the distribution of photosynthetic products into fruits and increased yield. Using three pipes for four rows was also beneficial to distribute more photosynthetic products into fruits and increase yield. A soil of 70%*F* could basically meet the water needs of muskmelon and enhanced yield due to an increase in the fruits' fresh biomass. In general, the optimal combination of a half plastic covering and one pipe for two rows, and the sub-optimal combination of a half plastic covering and three pipes for four rows, as well as a lower limit of irrigation of 70%*F*, are recommended in muskmelon cultivation, as they can improve *Pn*, the photosynthetic product distribution, and yield.

Supplementary Materials: The following are available online at www.mdpi.com/2077-0472/10/3/84/s1, Figure S1: Influence of experimental factor on muskmelon yield, Table S1: L9 (3^4), Table S2: Irrigation amount and water use efficiency, Table S3: Effect of plastic covering method, drip irrigation pipe density and lower limit of irrigation on transpiration rate (T_r) ($\mu molCO_2 \cdot m^{-2} \cdot s^{-1}$) and intercellular CO_2 concentration (C_i) ($\mu mol \cdot mol^{-1}$), Table S4: Nitrogen uptake of different organs of muskmelon ($g \cdot kg^{-1}$), Table S5: Correlation analysis of biomass and yield.

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