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Magnesium Fertilizer Application and Soil Warming Increases Tomato Yield by Increasing Magnesium Uptake under PE-Film Covered Greenhouse

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Abstract: Magnesium (Mg) plays an important role in numerous physiological and biochemical processes in plants. However, Mg deficiency is common worldwide, especially in greenhouse vegetable systems, due to the overuse or misuse of fertilizers. This study investigated the effects of different Mg application strategies in alleviating Mg deficiency of tomatoes in PE-film covered greenhouse. Six field treatments were used: conventional fertilization practice (C), conventional fertilization + soil warming (CW), conventional fertilization + Mg applied to soil (C + MgS), conventional fertilization + Mg applied as foliar application (C + MgF), conventional fertilization + Mg applied to soil and foliar application (C + MgSF), and conventional fertilization + Mg applied to soil and foliar application with soil warming (C + MgSFW). Foliar spray of Mg fertilizer (C + MgF, C + MgSF, and C + MgSFW) increased the total Mg uptake and Mg content of functional leaves in both winter-spring and autumn-winter seasons. Soil warming treatments (CW and C + MgSFW) were also beneficial for Mg uptake and chlorophyll biosynthesis compared with no-warming treatments (C and C + MgSF), especially in autumn-winter season. Additionally, Mg fertilizer application and soil warming increased tomato yields; the C + MgSFW treatment had the highest increase in yields compared with the C treatment. Therefore, foliar Mg fertilizer application combined with soil warming, while considering seasonal variation, is feasible for reducing Mg deficiency in tomatoes under PE-film covered greenhouse vegetable systems.

Keywords: foliar spray; Mg deficiency; *Lycopersicon esculentum* Mill.; temperature; yield production

1. Introduction

The areas with low available soil Mg content in China are mainly located south of the Yangtze River; it is generally believed that the soil in the northern Chinese region is rich in Mg because of low rainfall and weak leaching [1,2]. However, Mg deficiency in greenhouse vegetable crops in northern China has occurred frequently in recent years, leading to a decrease in crop yield [3–5].

The main reason for Mg deficiency is that the Mg absorbed by crops from the soil is not replenished, and too much nitrogen, phosphorus, and potassium are applied to greenhouse fields, resulting in an imbalance in the soil nutrients, especially the excessive K/Mg ratio in the soil, leading to a Mg deficiency in crops [3,6–8]. For example, the unbalanced nutrients in greenhouse soils in Shouguang, Shandong Province, China, are reflected as a surplus of nitrogen, phosphorus, and potassium, which has reached the following values: 1531 kg ha^{-1} N, 1701 kg ha^{-1} P_2O_5, and 539.6 kg ha^{-1} K_2O [9]. In addition, according to our preliminary investigation, Mg deficiency was more likely to occur in the autumn-winter season during the greenhouse tomato cultivation in Shouguang, Shandong Province, China. Solar greenhouses, which are the dominant type of vegetable production system covered with polyethylene foliage in China, are typically 70–100 m long and 7–12 m wide. During winter, greenhouses are additionally covered with carpets made of straw at night but do not have any heating function, and this low soil temperature can limit crop nutrient absorption [8,10,11]. Many studies have shown that applying Mg fertilizers can improve Mg absorption in tomatoes, which is reflected by the content increase of chlorophyll and Mg in the tomato leaves as well as the growth of tomato yield; however, most of these reports are substrate, pot, or hydroponic cultures, and there are scarce results from field experiments, especially in field under greenhouse cover [4,12,13].

Therefore, this study was carried out to investigate the effects of different methods of Mg fertilizer application, including soil application, foliar application, soil warming, and their combination on improving Mg nutrition in greenhouse tomatoes, to provide a reference for practical production.

2. Materials and Methods

2.1. Description of the Experimental Site

The field experiment under PE-film covered greenhouse was conducted in Shouguang City, Shandong Province, China (36°55 N, 118°45 E) from February 2010 to January 2011. A typical vegetable greenhouse (ground area, 73.0 × 11.5 m^2), which has been converted to grow tomatoes for 2 years, was selected for the experiment. The soil samples were collected and analyzed at the beginning of the experiment, and the soil characteristics at the study site are listed in Table 1.

Table 1. Soil characteristics at the experimental field.

Soil Layer (cm)	pH	Alkali-N (mg kg^{-1})	Olsen-P (mg kg^{-1})	Available K (mg kg^{-1})	Organic Matter (g kg^{-1})	Exchangeable Ca (cmol kg^{-1})	Exchangeable Mg (cmol kg^{-1})
0–30	6.41	76.1	118	232	14.4	14.4	3.2
30–60	6.33	92.3	55	183	13.0	13.4	2.7
60–90	6.40	104.3	28	163	9.5	12.0	2.2

2.2. Experimental Design and Crop Management

Annual double-cropping of tomatoes (*Lycopersicon esculentum* Mill.) including winter-spring (WS, from February to June) and autumn-winter (AW, from August To January of the following year) seasons was conducted in the same field under PE-film covered greenhouse. The large-fruited tomato varieties planted during the WS and AW seasons were 'Hongluoman' and 'Labi', respectively. The experiment was designed with six treatments: C, the local farmer conventional fertilization practice; CW, conventional fertilization + soil warming; C + MgS, conventional fertilization + Mg applied to soil; C + MgF, conventional fertilization + Mg applied as foliar application; C + MgSF, conventional fertilization + Mg applied to soil and foliar application; C + MgSFW, conventional fertilization + Mg applied to soil and foliar application with soil warming. A completely randomized design with three replications was used in 2010 and 2011, and each plot size was 32.2 m^2.

Mg fertilizer was applied by incorporating 150 kg ha^{-1} magnesium sulfate into the soil before transplantation during the AW and WS seasons. Foliar spray of Mg fertilizer was conducted by spraying 1125 L ha^{-1} magnesium sulfate solution (1%, v/v) to the leaves thrice every other 6 days by using a hand sprayer before blooming of first flower cluster. For the soil warming treatment, 110 m of 1000 W heating cables were buried in the soil (depth: 20–25 cm) and set at 25 °C before transplanting, covering a plot area of 4 m^2. Soil warming was started directly after the flowering of the first flower cluster with a heating regime of 06:00 am–17:30 pm each day and lasted continuously for 30 days, from March 23 to April 22 and October 15 to November 15 in the WS and AW seasons, respectively.

Following the local farmers' practice, fermented pig manure (1.8% N, 1.8% P_2O_5, 1.6% K_2O) at rates of 15 t ha^{-1} was applied as basal fertilizers for each season, which supplied approximately 268 kg ha^{-1} of N, 271 kg ha^{-1} of P_2O_5, and 246 kg ha^{-1} of K_2O, respectively. P fertilizer (superphosphate, 12% P_2O_5) and K fertilizer (potassium sulfate, 50% K_2O) as basal fertilizers were also applied to the soil by plowing before transplanting.

N fertilizer (urea, 46% N) was dissolved and top-dressed with furrow irrigation; irrigation was conducted 10 and 12 times in the WS and AW seasons, respectively. The amounts of applied urea, superphosphate, and potassium sulfate were 1061, 2125, and 1278 kg ha^{-1} in the WS season, and 983, 2125, and 1208 kg ha^{-1} in the AW season, respectively.

2.3. Sample Collection and Analysis

The soil characteristics were determined by the following methods. Soil pH was determined using water extraction, and the ratio of water to soil is 5:1 (v/w). Soil alkali-N, available P, and available K were determined according to the diffusion absorption method, Olsen method, and NH_4OAc extract-flame photometric method, respectively [14]. Organic matter was measured by oil bath heating dichromate oxidation method. Exchangeable Ca and Mg were analyzed using an atomic absorption spectrophotometer (AA-7000, Shimadzu, Kyoto, Japan).

The air temperature at 1 m above the ground in the greenhouse and soil temperature at a depth of 20 cm in each plot were measured from 8:30 am to 10:00 am. Functional leaves, which are the first matured leaves below the 2nd–5th fruit cluster, were collected at different vegetative growth stages before topping, and then carefully washed with tap water for further analysis. The chlorophylls were extracted using a 95% (v/v) ethanol solution from fresh tomato leaves, and then the absorbances of extracts were measured at 663 and 645 nm using a spectrophotometer (UV-1601, Rayleigh Ltd., Beijing, China) to determine the total chlorophyll content [15]. During the final harvesting stages, plant and fruit samples were collected, oven-dried at 75 °C for at least 48 h, and then ground to fine powder for nutrient analysis. The total N content was determined by the Kjeldahl method [16]. Total P content was determined by the vanadium molybdate yellow colorimetric method after digestion with concentrated H_2SO_4/H_2O_2 [17]. Total K content was analyzed using flame photometer (Taomsun-6400A, Shanghai, China). The Mg content was analyzed using an atomic absorption spectrophotometer. The nutrient uptake by plants were calculated by multiplying the total weights of tomato samples and their nutrient concentrations. The K/Mg ratio was calculated by their equivalent weight in the leaves. For each plot, the tomatoes were picked and weighed at each harvest, and the total yield was calculated as the cumulative weight of tomatoes from all harvest days.

2.4. Statistical Analysis

All data were analyzed using the SPSS software (SPSS Inc., Chicago, IL, USA). Analysis of variance was applied to determine the significance among the treatments. The data were analyzed using one-way ANOVA for WS and AW seasons, respectively, and the least significant difference test was employed to determine significant differences between treatments at $p < 0.05$.

3. Results

3.1. Changes in Soil Temperature and Greenhouse Temperature

The air temperature in the tomato greenhouse during the WS season increased gradually and finally reached a balance at approximately 24 °C, while the temperature during the AW season decreased gradually and reached 15 °C at the end of harvest in January (Figure 1a). A similar trend in soil temperature was also found in the unheated tillage layer in the greenhouse (Figure 1b). The rootzone soil temperature during the WS season increased from 18.2 °C in mid-March to 22.8 °C, while that during the AW season decreased from 23 °C in mid-September to 14.5 °C at the end of the harvest. The average temperature of the rootzone without heating was 21.5 °C during the WS season, which was higher than that during the AW season (19.2 °C) at the fruit enlargement stage (Figure 2). For the soil warming treatments, the average daily soil temperatures of the rootzone at the fruit expansion stage were 23.1 °C and 22.1 °C during the WS and AW seasons, respectively, which were 3–5 °C higher than that in the unheated soil.

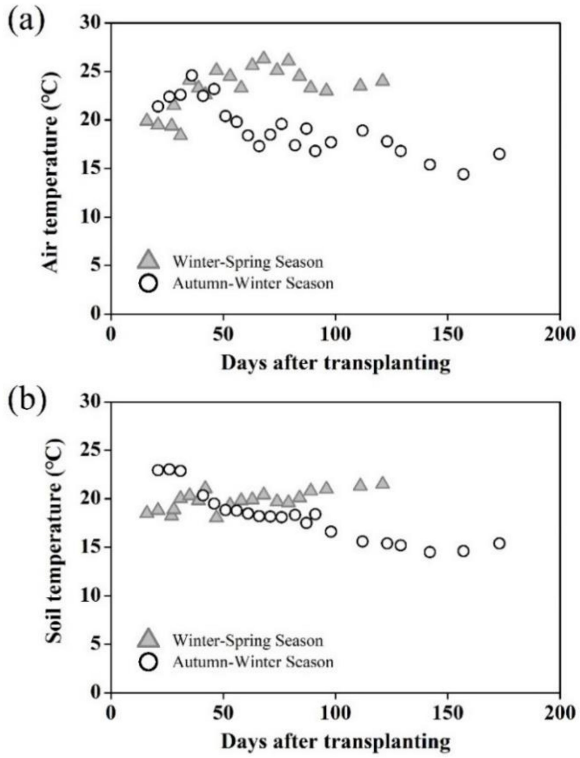

Figure 1. Air temperature at 1 m above the ground measured at 8:30–10:00 a.m. in tomato greenhouse (**a**). Soil temperature at a depth of 20 cm measured at 8:30–10:00 a.m. in tomato greenhouse (**b**).

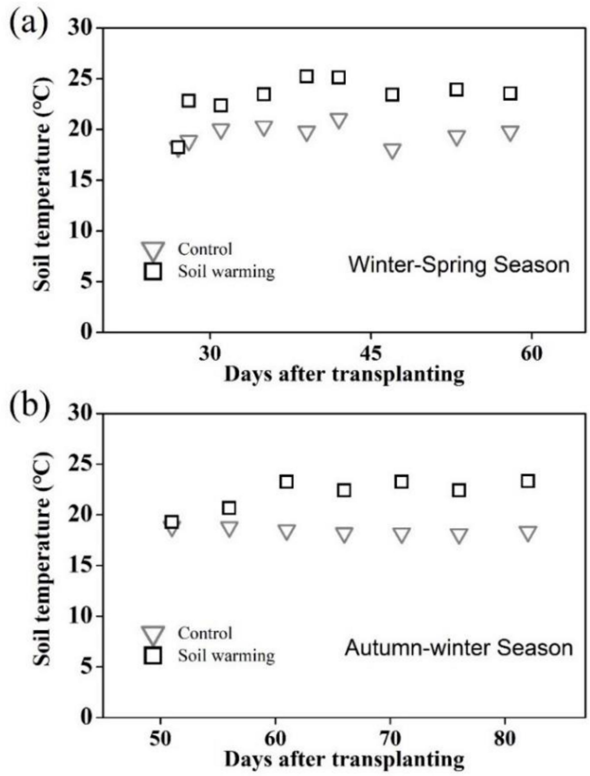

Figure 2. Soil temperature at a depth of 20 cm measured at 8:30–10:00 a.m. after soil warming in winter-spring season (**a**) and autumn-winter season (**b**).

3.2. Effects of Mg Fertilizer Application on Mg and Potassium Contents in the Functional Leaves of Tomatoes

The changes in K and Mg content of the tomato functional leaves at different periods are shown in Table 2. The C + MgF, C + MgSF, and C + MgSFW treatments significantly increased the Mg content in functional leaves compared with the C and C + MgS treatments during both the WS and AW seasons, but no significant differences were found between the C and C + MgS treatments. Compared with the C treatment, the average Mg content of the functional leaves in the C + MgF, C + MgSF, and C + MgSFW treatments increased by 10.6%, 10.0%, and 10.5% during the WS season, and by 6.6%, 7.6%, and 14.5% during the AW season, respectively.

The CW treatment significantly increased the Mg content of functional leaves by 6.3% and 21.8% during the WS season and by 12.5% and 10.0% during the AW season in the third and fourth functional leaves, respectively, as compared with the C treatment. However, compared with C + MgSF, the C + MgSFW treatment only significantly increased the Mg content of functional leaves by 9.5% and 8.7%, respectively, in the fourth and fifth functional leaves during the AW season. The above results indicate that soil warming could improve the Mg absorption by tomatoes. Generally, the Mg content of functional leaves during the WS season was 2–3 fold higher than that during the AW season, which was probably due to the higher soil temperature during the WS season.

Application of Mg fertilizer without soil warming had no significant effects on the K content in the functional leaves of tomatoes during the WS season; however, the C + MgSFW treatment significantly decreased the K content in the functional leaves by 29.74% and 32.4% in the third and fourth functional leaves, respectively, compared with the C + MgSF treatment. The K contents of the functional leaves in the second and third fruit clusters under Mg fertilizer application treatments with or without soil warming were all lower than those under C treatment.

In general, the application of Mg fertilizers as well as warming tended to increase the Mg content and decrease the K content in functional leaves, resulting in a decrease in the K/Mg ratio in the functional leaves. The most significant decrease in the K/Mg ratio appeared under the C + MgSFW treatment, which decreased the ratio by 30.6% and 29.4%, on average, during the WS and AW seasons, respectively.

3.3. Effects of Mg Fertilizer Application on Total Chlorophyll Content of Tomato Leaves

The total chlorophyll content in the functional leaves of tomatoes from different functional leaves is shown in Table 3. During the WS season, there were no significant differences in the total chlorophyll contents of the functional leaves between the different treatments, except for the fourth fruit cluster. During the AW season, the total chlorophyll contents of functional leaves under the C + MgF, C + MgSF, C + MgSFW, and CW treatments were significantly higher than those under the C + MgS and C treatments; the CW treatment significantly increased the total chlorophyll content by 29.2% in the third functional leaves compared with the C treatment, while the C + MgSFW treatment significantly increased the chlorophyll content of functional leaves by 5.2% and 13.7%, respectively, in the second and third functional leaves, compared with the C + MgSF treatment. During the AW season, it was found that the total chlorophyll contents were higher under the Mg spray treatments (C + MgF, C + MgSF, and C + MgSFW) than those under other treatments, and those of the soil warming treatments were higher than those under the non-warming treatments.

Table 2. The Mg and K contents (g kg^{-1}) and K/Mg ratio in functional leaves in two tomato seasons at different growth periods.

	Treatment	Sampling Date								Average
		2d Functional Leaves		3rd Functional Leaves		4th Functional Leaves		5th Functional Leaves		
		WS	AW	WS	AW	WS	AW	WS	AW	
Mg	C	6.3 ± 0.0 bc	2.8 ± 0.04 b	6.3 ± 0.3 c	2.4 ± 0.1 c	5.5 ± 0.9 b	2.0 ± 0.03 d	6.3 ± 0.3 a	2.1 ± 0.16 c	4.2
	CW	6.1 ± 0.4 c	2.7 ± 0.05 c	6.7 ± 0.1 ab	2.7 ± 0.12 ab	6.7 ± 0.2 a	2.2 ± 0.01 b	6.4 ± 0.3 a	2.2 ± 0.02 bc	4.5
	C + MgS	6.6 ± 0.3 ab	2.7 ± 0.04 c	6.3 ± 0.2 c	2.3 ± 0.47 c	6.4 ± 0.2 a	2.0 ± 0.05 d	6.7 ± 0.2 a	2.2 ± 0.02 bc	4.4
	C + MgF	6.8 ± 0.0 a	2.9 ± 0.04 a	7.0 ± 0.1 a	2.6 ± 0.04 b	6.6 ± 0.2 a	2.1 ± 0.01 c	6.5 ± 0.4 a	2.3 ± 0.04 b	4.6
	C + MgSF	7.0 ± 0.2 a	2.9 ± 0.06 a	6.7 ± 0.2 ab	2.7 ± 0.03 ab	6.4 ± 0.1 a	2.1 ± 0.02 c	6.7 ± 0.1 a	2.3 ± 0.07 b	4.6
	C + MgSFW	6.9 ± 0.3 a	3.0 ± 0.07 a	6.8 ± 0.1 ab	2.8 ± 0.07 a	6.5 ± 0.1 a	2.3 ± 0.01 a	6.7 ± 0.1 a	2.5 ± 0.03 a	4.7
K	C	30.3 ± 1.7ab	46.5 ± 1.7 a	39.0 ± 4.0 a	49.6 ± 1.6 a	39.8 ± 5.1 a	21.9 ± 1.9 c	29.6 ± 8.4 ab	16.9 ± 1.9 ab	34.2
	CW	29.0 ± 3.4 b	38.1 ± 1.7 b	36.5 ± 3.4 a	35.8 ± 2.1 b	26.2 ± 3.4 a	17.2 ± 2.3 d	23.1 ± 2.1 bc	14.8 ± 2.5 b	27.6
	C + MgS	32.3 ± 3.3 ab	42.7 ± 4.3 ab	41.2 ± 0.7 a	38.9 ± 0.1 b	40.1 ± 3.0 a	33.5 ± 2.7 a	32.3 ± 1.2 a	19.9 ± 2.3 a	35.1
	C + MgF	29.9 ± 1.7 ab	38.1 ± 1.7 b	37.3 ± 1.0 a	33.7 ± 0.4 b	33.7 ± 2.6 a	27.6 ± 2.9 b	27.7 ± 2.7 a	18.3 ± 1.9 ab	30.8
	C + MgSF	30.9 ± 1.1 ab	37.2 ± 6.4 b	37.7 ± 2.0 a	34.5 ± 7.7 b	37.0 ± 1.1 a	19.3 ± 1.0 cd	28.0 ± 2.2 a	20.5 ± 2.0 a	30.6
	C + MgSFW	33.1 ± 1.0 a	36.2 ± 3.6 b	28.1 ± 3.6 b	35.1 ± 1.1 b	26.9 ± 4.8 b	20.0 ± 2.2 cd	21.2 ± 1.9 c	15.8 ± 0.4 b	27.1
K/Mg	C	4.8 ± 0.2 a	16.8 ± 0.4 a	6.2 ± 0.5 a	20.3 ± 0.4 a	7.5 ± 2.0 a	10.7 ± 1.1 a	4.7 ± 1.5 a	8.0 ± 0.7 a	9.9
	CW	4.7 ± 0.4 a	14.0 ± 0.8 c	5.4 ± 0.5 b	13.5 ± 1.3 c	3.9 ± 0.4 c	7.8 ± 1.0 d	3.6 ± 0.5 ab	6.6 ± 1.1 bc	7.4
	C + MgS	4.9 ± 0.7 a	16.1 ± 1.9 ab	6.5 ± 0.2 a	17.3 ± 4.0 ab	6.3 ± 0.6 ab	16.4 ± 0.9 b	4.8 ± 0.2 a	9.1 ± 1.1 a	10.2
	C + MgF	4.4 ± 0.2 a	13.2 ± 0.6 bc	5.3 ± 0.2 b	13.0 ± 0.2 bc	5.1 ± 0.5 b	13.1 ± 1.4 c	4.3 ± 0.7 ab	8.1 ± 0.7 ab	8.3
	C + MgSF	4.4 ± 0.1 a	12.6 ± 1.9 c	5.6 ± 0.1 b	12.6 ± 2.7 c	5.8 ± 0.2 bc	9.0 ± 0.5 cd	4.2 ± 0.4 ab	9.0 ± 0.6 ab	7.9
	C + MgSFW	4.8 ± 0.4 a	12.2 ± 1.5 c	4.1 ± 0.5 c	12.4 ± 0.7 c	4.1 ± 0.7 c	8.6 ± 0.9 d	3.1 ± 0.3 b	6.2 ± 0.1 c	6.9

Different letters in the same column means significant differences between different treatments at $p < 0.05$.

Table 3. The total chlorophyll contents of functional leaves in different treatments of Mg fertilizers application (mg g^{-1}).

Treatment	Sampling Date								Average
	2nd Functional Leaves		3rd Functional Leaves		4th Functional Leaves		5th Functional Leaves		
	WS	AW	WS	AW	WS	AW	WS	AW	
C	1.42 ± 0.25 a	1.76 ± 0.04 d	1.78 ± 0.03 a	1.37 ± 0.07 d	1.87 ± 0.04 ab	1.81 ± 0.031 b	1.69 ± 0.081 a	1.61 ± 0.138 a	1.66
CW	1.47 ± 0.06 a	1.77 ± 0.06 d	1.74 ± 0.08 a	1.77 ± 0.20 ab	1.97 ± 0.185 ab	1.83 ± 0.196 b	1.71 ± 0.062 a	1.69 ± 0.201 a	1.74
C + MgS	1.56 ± 0.23 a	1.40 ± 0.02 e	1.74 ± 0.18 a	1.47 ± 0.08 cd	1.94 ± 0.119 ab	1.82 ± 0.045 b	1.72 ± 0.066 a	1.71 ± 0.069 a	1.67
C + MgF	1.46 ± 0.12 a	1.85 ± 0.05 c	1.80 ± 0.05 a	1.72 ± 0.08 ab	1.67 ± 0.326 b	1.82 ± 0.044 b	1.74 ± 0.04 a	1.67 ± 0.026 a	1.72
C + MgSF	1.58 ± 0.15 a	1.94 ± 0.07 b	1.84 ± 0.27 a	1.61 ± 0.07 bc	1.96 ± 0.299 ab	1.96 ± 0.102 ab	1.78 ± 0.173 a	1.73 ± 0.081 a	1.80
C + MgSFW	1.57 ± 0.25 a	2.04 ± 0.03 a	1.91 ± 0.28 a	1.83 ± 0.03 a	2.11 ± 0.147 a	2.02 ± 0.055 a	1.83 ± 0.195 a	1.80 ± 0.116 a	1.89

Different letters in the same column means significant differences between different treatments at $p < 0.05$.

3.4. Effects of Mg Fertilizer Application on Nutrient Absorption by Tomatoes

It can be seen that Mg application and soil warming had large effects on nutrient absorption (Table 4). Compared with the C treatment, the N and P uptake by tomatoes was improved by Mg application and soil warming treatments during both the WS and AW seasons, and the spraying of Mg fertilizer on leaves was more beneficial for the uptake of N and P compared with soil application. The K uptake by tomatoes in the soil warming treatments (CW and C + MgSFW) was lower than that under the C treatment during the WS season, while the opposite results were observed during the AW season.

Table 4. The total nutrient uptake of tomato plants in different treatments of Mg fertilizers application (g plant^{-1}).

Treatment	N			P			K			Mg		
	WS	AW	Average	WS	AW	Average	WS	AW	Average	WS	AW	Average
C	6.18	4.78	5.48	1.48	1.22	1.35	9.84	9.02	9.43	0.43	0.19	0.31
CW	6.28	6.29	6.29	1.50	1.40	1.45	7.65	10.15	8.90	0.48	0.23	0.36
C + MgS	6.56	5.13	5.85	1.44	1.06	1.25	10.09	9.62	9.86	0.43	0.22	0.33
C + MgF	7.48	5.75	6.62	1.67	1.48	1.58	10.23	9.68	9.96	0.50	0.24	0.37
C + MgSF	7.55	6.40	6.98	1.84	1.59	1.72	12.11	9.91	11.01	0.53	0.24	0.39
C + MgSFW	7.56	6.28	6.92	1.55	1.33	1.44	8.23	9.91	9.07	0.60	0.25	0.43

The Mg uptake by tomato plants under Mg fertilizer application treatments was higher than that under the C treatment, and the soil warming treatments were more beneficial for Mg uptake by tomato plants than non-warming treatments. There were no significant differences between the C + MgS and C treatments during the WS season and the C + MgSF and C + MgF treatments during the AW season, indicating that Mg fertilizer application to the soil had little effect on Mg uptake by plants. The Mg uptake by tomato plants under Mg spray treatments (C + MgF, C + MgSF, and C + MgSFW) increased by 16.3%, 23.3%, and 39.5%, respectively, with an average of 26.3% during the WS season and by 26.3%, 26.3%, and 31.6%, respectively, with an average of 28.1% during the AW season.

3.5. Effects of Different Treatments on Tomato Yield

As shown in Table 5, compared with the C treatment, the Mg fertilizer application treatments increased the tomato yields, of which the highest yield was found in the C + MgSFT treatment with 15.7% and 19.4% increases, respectively, during the WS and AW seasons. Soil warming treatments (CW and C + MgSFW) also significantly increased tomato yields compared to no-warming treatments, except for those between CW and C treatments during the WS season. The average yield in the soil warming treatments (CW and C + MgSFW) was 8.2% and 5.7% higher than those in the C and C + MgSF treatments, respectively. In addition, foliar spraying of Mg fertilizers had more beneficial effects on tomato yields than did soil application.

Table 5. Tomato yield under different treatments of Mg fertilizers application (t ha^{-1}).

Treatment	WS	AW	Total of Two Seasons
C	84.3 ± 2.9 c	103.5 ± 3.2 c	187.8 ± 6.0 c
CW	86.9 ± 2.5 c	116.2 ± 2.3 b	203.2 ± 4.0 b
C + MgS	87.0 ± 1.2 c	117.2 ± 6.1 b	204.1 ± 5.2 b
C + MgF	91.0 ± 1.1 b	120.4 ± 2.0 ab	211.5 ± 2.7 b
C +MgSF	93.0 ± 1.7 b	116.0 ± 2.3 b	209.0 ± 3.7 b
C + MgSFW	97.3 ± 3.3 a	123.5 ± 3.4 a	220.9 ± 6.4 a

Different letters in the same column means significant differences between different treatments at $p < 0.05$.

4. Discussion

Mg is an essential nutrient element for plants, and Mg deficiency can change the metabolism of active oxygen, photosynthesis, and distribution of assimilates in crops, which will ultimately affect the yield and quality of agricultural products [4,18,19]. According to a meta-analysis of 70 years of research, the dry matter formation of species is inhibited when leaf Mg concentrations are lower than 0.35% [20]. In this study, the leaf Mg concentration under the control treatment ranged from 5.5 to 6.3 g kg^{-1} and 2.0 to 2.8 g kg^{-1} during the WS and AW seasons, respectively (Table 2), indicating that tomato Mg deficiency occurred during the AW season. Application of Mg fertilizer can improve the Mg nutrition of crop plants, increase the chlorophyll and Mg contents in leaves, and thus, increase crop yield [21–24]. In this experiment, the three Mg spray treatments (C + MgF, C + MgSF, and C + MgSFW) all had a significant effect, and the total chlorophyll and Mg contents in leaves, Mg absorbed by tomatoes, and tomato yield were all higher than those under control treatment. Among the three treatments, C + MgSFW showed the best effect on Mg improvement (Tables 2 and 3). The average yield of greenhouse tomatoes varied from 88 t ha^{-1} to 108 t ha^{-1} according to the study by Lv et al. [25], which was similar to the results of the present study. These results indicate that the yields obtained in our study were typical grower yields in the mentioned area. Therefore, foliar Mg application and soil warming are two effective strategies to increase tomato yields by enhancing Mg uptake and the subsequent chlorophyll content of tomato under PE-film covered greenhouse.

However, under the soil application of Mg treatment, the tomato yield was close to that under control treatment, and the yield increase was lower than that under the Mg spray treatment (Table 5). In this experiment, 150 kg ha^{-1} of $MgSO_4$ was applied to soil, which was the same amount used in the experiment conducted by Li et al. in Shijiazhuang [26]; however, no similar yield increase was observed. Comparing the two experiments, it can be found that the available soil K content in this experiment was 232 mg kg^{-1}, whereas it was 126 mg kg^{-1} in the experiment by Li et al. [26], indicating that Mg uptake was seriously inhibited by high soil K levels, which were caused by a high K fertilizer usage in the present study. Soil investigation suggested that planting tomatoes in soil with high available K content and high K/Mg ratio could reduce Mg content in leaves and tomato yield. The antagonistic levels of K and Mg may be the reason behind the Mg deficiency in crops [8,13,22]. According to a study by Li et al. [22], when the K/Mg ratio was increased from 4:1 to 8:1, the total biomass and Mg uptake of tomatoes decreased significantly, confirming that high K levels inhibited Mg uptake and plant growth. This phenomenon has been reported in some previous studies, wherein the ratios between elements could affect the nutrient uptake by plants [27,28]. Therefore, in this experiment, soil Mg application could not effectively alleviate the magnesium deficiency of tomato plants, which may be mainly due to the relatively high content of K in soil, resulting the inhibitory impacts on the Mg uptake by tomato roots; however, the foliar spraying of Mg fertilizer can directly increase the Mg uptake and accumulation in tomato leaves under PE-film covered greenhouse.

In North China, the PE-film covered greenhouses are commonly covered with carpets made of straw at night but do not have any heating function, resulting the lower soil temperature especially in the cold season. Numerous studies have found a close relationship between Mg uptake and soil temperature, and the lower temperature is an important cause of Mg deficiency in tomato [8,29]. The normal temperature for tomatoes to grow and development is 15–25 °C. In this experiment, the soil warming measures were able to raise the rootzone temperature by 3–5 °C, and the daily average temperature of the rootzone during the warming period reached 23.1 °C during the WS season and 22.1 °C during the AW season (Figure 2). Compared with the control treatment, the Mg uptake by plants, chlorophyll content in leaves, and tomato yield under soil warming treatments all improved in the Mg fertilizer application treatments, and the yield increase reached a significant level, especially during the AW season, indicating that soil warming is conducive to improving the Mg nutrition of tomatoes. Some studies have shown that inhibiting transpiration can reduce nutrient absorption and biomass of tomatoes [30–32]. Further studies are needed to clarify whether the effect of low temperature on Mg absorption by tomatoes is caused by transpiration inhibition. Different tomato varieties have different nutrient absorption capabilities [33,34]. The results of this experiment showed that the Mg content in leaves and Mg amount consumed by tomatoes during the WS season (variety: Hongluoman) were 2 to 3 times higher than those during the AW season (variety: Labi), which were probably caused by the difference in varieties. Increasing the application of Mg fertilizer can increase tomato yield and farmer income [19,35,36]. In addition, soil warming was also beneficial for the increased tomato yield (Table 5). Therefore, soil warming is also a recommended method to increase tomato yield by improving soil Mg availability under PE-film covered greenhouse.

5. Conclusions

Mg fertilizer application treatments obviously improved tomato yields by increasing Mg uptake, wherein the combination of foliar spray and soil warming treatment showed the best effect compared with the control. Foliar spray of Mg fertilizer can directly increase Mg absorption of tomato plants by avoiding the interferences of high K content in soils. Soil warming can improve soil temperature and thereby indirectly enhance Mg uptake by plants via improving soil Mg availability. In addition, Mg fertilizer application and soil warming also largely improved chlorophyll content in tomato leaves, which was mainly due to the high Mg content and availability under PE-film covered greenhouse. Therefore, foliar spraying of Mg fertilizer and soil warming can increase chlorophyll content and subsequent tomato yields via directly increasing the Mg uptake by leaves or indirectly enhancing soil Mg availability (Figure 3), which are two effective ways to reduce Mg deficiency of tomato plants under PE-film covered greenhouse.

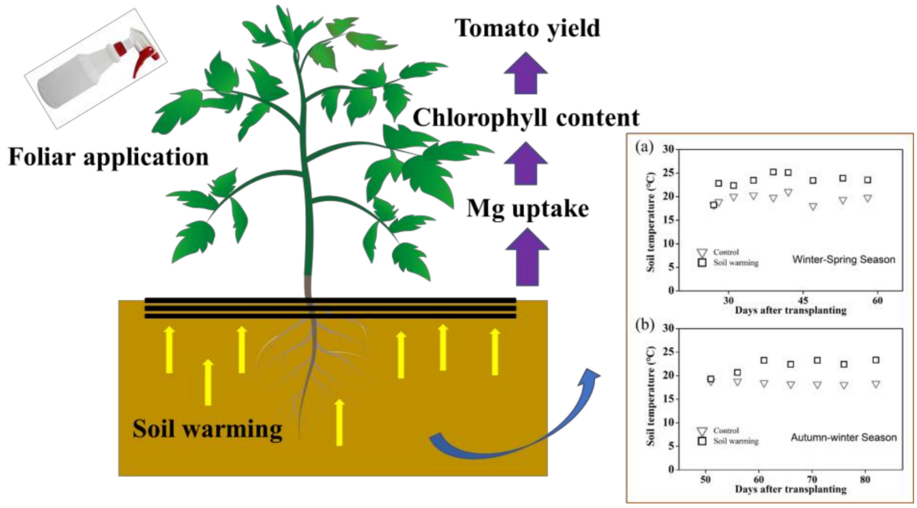

Figure 3. The combined strategy of foliar spray and soil warming could increase Mg content and yield of tomato by directly increasing the Mg uptake by leaves and indirectly enhancing soil Mg availability caused by high soil temperature, respectively.

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