Magnesium Fertilizer Application and Soil Warming Improves Magnesium Absorption and Yield of Tomatoes in Greenhouse

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Research Article

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Abstract

**Background:** Magnesium (Mg) is an essential macronutrient that 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 aimed to investigate different Mg application strategies for alleviating Mg deficiency in tomatoes grown in a greenhouse vegetable system.

**Methods:** Six field treatments were used: the farmer conventional fertilization practice (CK), CK + soil application of Mg fertilizer (MgS), CK + foliar spray of Mg fertilizer (MgF), CK + the combination of soil and foliar spray of Mg fertilizer (MgSF), CK + soil warming (T), and MgSF + soil warming (MgSFT).

**Results:** The results showed that the foliar spray of Mg fertilizer treatments (MgF, MgSF, and MgSFT) increased the total Mg uptake and Mg content of functional leaves in both winter-spring and autumn-winter seasons. Soil warming treatments (T and MgSFT) were also beneficial for Mg uptake and chlorophyll biosynthesis compared with no-warming treatments (CK and MgSF), especially in the autumn-winter season. Additionally, Mg fertilizer application and soil warming increased tomato yields; the MgSFT treatment had the highest increase in yields compared with the CK treatment.

**Conclusion:** Therefore, foliar Mg fertilizer application combined with soil warming, while considering seasonal variation, is feasible for reducing Mg deficiency in tomatoes under greenhouse vegetable systems.

**Background**

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: 1668 kg ha⁻¹ N, 1801 kg ha⁻¹ P₂O₅, and 20 kg ha⁻¹ K₂O [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 spray, soil warming, and their combination on improving Mg nutrition in greenhouse tomatoes, to provide a reference for practical production.

**Materials And Methods**

**Description of the experimental site**

The field experiment 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 m²), which has been used 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 layer (cm) | pH<sup>a</sup> | Alkaline hydra-N (mg kg<sup>−1</sup>) | Olsen-P (mg kg<sup>−1</sup>) | NH<sub>4</sub>OAc-K (mg kg<sup>−1</sup>) | Organic matter (mg kg<sup>−1</sup>) | Exchangeable Ca (cmol kg<sup>−1</sup>) | Exchangeable Mg (cmol kg<sup>−1</sup>) |
|-----------------|---------------|-------------------------------------|-----------------------------|-----------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|
| 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                                  |

<sup>a</sup>pH is determined using water extraction, and the ratio of water to soil is 5:1 (v/w).

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. The large-fruited tomato varieties planted during the WS and AW seasons were 'Hongluoman' and 'Labi', respectively. The experiment was designed with six treatments: CK, which is the local farmer conventional fertilization practice without Mg fertilizer application; MgS, which is similar to CK with soil application of Mg fertilizer; MgF, which is similar to CK with foliar spray of Mg fertilizer; MgSF, which is similar to CK with soil application and foliar spray of Mg fertilizer; T, which is the same fertilizer practice as in CK with soil warming; MgSFT, which has the same fertilizer practice as in MgSF with soil warming. A completely randomized design with three replications was used in 2010 and 2011, and each plot size was 32.2 m<sup>2</sup>.

Mg fertilizer was applied by incorporating 150 kg ha<sup>−1</sup> magnesium sulfate into the soil before transplantation during the AW and WS seasons. Foliar spray of Mg fertilizer was conducted by spraying 1% magnesium sulfate solution to the leaves thrice every other 6 days by using a hand sprayer before blooming. 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<sup>2</sup>. Soil warming was started directly after the flowering of the first flower cluster with a heating regime of 06:00–17:30 HR each day and lasted continuously for about 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, P fertilizer (superphosphate, 12% P<sub>2</sub>O<sub>5</sub>), and K fertilizer (potassium sulfate, 50% K<sub>2</sub>O) were applied to the soil by plowing before transplanting, which supplied approximately 268 kg ha<sup>−1</sup> of N, 671 kg ha<sup>−1</sup> of P<sub>2</sub>O<sub>5</sub>, and 246 kg ha<sup>−1</sup> of K<sub>2</sub>O, respectively. The applied amounts of chemical fertilizers were 488–225–639 (N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O) and 452–225–604 (N–P<sub>2</sub>O<sub>5</sub>–K<sub>2</sub>O) kg ha<sup>−1</sup> in the WS and AW seasons, respectively. N fertilizer was dissolved and top-dressed with furrow irrigation; irrigation was conducted 10 and 12 times in the WS and AW seasons, respectively.

Sample collection and analysis

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 HR. 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. Chlorophyll concentrations of a 95% (v/v) ethanol extract of fresh tomato leaves were determined using the method described by Arnon [14].

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; then, the N, P, K, and Mg contents were analyzed using an elemental analyzer (Costech ECH 4024, Picarro, Italy). 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.
Statistical analysis

All data were analyzed using the SPSS software (SPSS Inc., Chicago, IL, USA). The data were analyzed using analysis of variance, and the least significant difference test was employed to determine significant differences between treatments at \( P < 0.05 \).

Results

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 (Fig. 1a). A similar trend in soil temperature was also found in the unheated tillage layer in the greenhouse (Fig. 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 (Fig. 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.

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 MgF, MgSF, and MgSFT treatments significantly increased the Mg content in functional leaves compared with the CK and MgS treatments during both the WS and AW seasons, but no significant differences were found between the CK and MgS treatments during both seasons. Compared with the CK treatment, the average Mg content of the functional leaves in the MgF, MgSF, and MgSFT 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.
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

| Treatments | Sampling Date          | Second functional leaves | Third functional leaves | Fourth functional leaves | Fifth functional leaves |
|------------|------------------------|--------------------------|-------------------------|-------------------------|------------------------|
|            |                        | WS          | AW          | WS          | AW          | WS          | AW          | WS          | AW          |
| Mg content |                        |              |             |             |             |             |             |             |             |
| CK         |                        | 6.3±0.0 bc  | 2.8±0.04 b  | 6.3±0.3 c  | 2.4±0.1 c  | 5.5±0.9 d  | 2.0±0.03 d  | 6.3±0.3 a  | 2.1±0.16 c  |
| T          |                        | 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 c  | 2.2±0.02 bc |
| 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 d  | 2.0±0.05 d  | 6.7±0.2 a  | 2.2±0.02 bc |
| 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 c  | 2.1±0.01 c  | 6.5±0.4 a  | 2.3±0.04 b  |
| 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 c  | 2.1±0.02 a  | 6.7±0.1 a  | 2.3±0.07 a  |
| MgSFT      |                        | 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  |
| K content  |                        |              |             |             |             |             |             |             |             |
| CK         |                        | 30.3±1.7 ab | 46.5±1.7 a  | 39.0±4.0 a  | 49.6±1.6 a  | 39.8±5.1 a | 21.9±1.9 a  | 29.6±8.4 ab| 16.9±1.9 ab |
| T          |                        | 29.0±3.4 b  | 38.1±1.7 b  | 36.5±3.4 a  | 35.8±2.1 a  | 26.2±3.4 a | 17.2±2.3 a  | 23.1±2.1 a | 14.8±2.5 a  |
| MgS        |                        | 32.3±3.3 ab | 42.7±4.3 ab | 41.2±0.7 a  | 38.9±0.1 a  | 40.1±3.0 a | 33.5±2.7 a  | 32.3±1.2 a | 19.9±2.3 a  |
| 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 |
| MgSF       |                        | 30.9±1.1 ab | 37.2±6.4 b  | 37.7±2.0 a  | 34.5±7.7 a  | 37.0±1.1 a | 19.3±1.0 cd | 28.0±2.2 a | 20.5±2.0 a  |
| MgSFT      |                        | 33.1±1.0 a  | 36.2±3.6 b  | 28.1±3.6 b  | 35.1±1.1 b  | 26.9±4.8 cd| 20.0±2.2 cd | 21.2±1.9 a | 15.8±0.4 a  |
| K/Mg ratio |                        |              |             |             |             |             |             |             |             |
| CK         |                        | 4.8±0.2 a   | 16.8±0.37 a | 6.2±0.5 a  | 20.3±0.41 a | 7.5±2.0 a  | 10.7±1.06 a | 4.7±1.5 a  | 8.0±0.67 a  |
| T          |                        | 4.7±0.4 a   | 14.0±0.84 c | 5.4±0.5 b  | 13.5±1.28 c | 3.9±0.4 c  | 7.8±1.04 d  | 3.6±0.5 a  | 6.6±1.10 bc |
| MgS        |                        | 4.9±0.7 a   | 16.1±1.87 ab| 6.5±0.2 a  | 17.3±3.97 a | 6.3±0.6 ab | 16.4±0.93 b | 4.8±0.2 a  | 9.1±1.09 a  |
| MgF        |                        | 4.4±0.2 a   | 13.2±0.63 bc| 5.3±0.2 b  | 13.0±0.16 bc| 5.1±0.5 bc | 13.1±1.40 bc| 4.3±0.7 a  | 8.1±0.72 ab |
| MgSF       |                        | 4.4±0.1 a   | 12.6±1.90 c | 5.6±0.1 b  | 12.6±2.67 c | 5.8±0.2 bc | 9.0±0.54 cd | 4.2±0.4 ab | 9.0±0.62 ab |
| MgSFT      |                        | 4.8±0.4 a   | 12.2±1.46 c | 4.1±0.5 c  | 12.4±0.67 c | 4.1±0.7 c  | 8.6±0.92 d  | 3.1±0.3 b  | 6.2±0.10 c  |

Different letters in the same column mean significant differences between different treatments at \(P < 0.05\).

The T 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 CK treatment. However, compared with MgSF, the MgSFT 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 MgSFT 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 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 CK 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 MgSFT treatment, which decreased the ratio by 30.6% and 29.4%, on average, during the WS and AW seasons, respectively.

Effects of Mg fertilizer application on chlorophyll content of the functional leaves of tomatoes

The 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 chlorophyll contents of the functional leaves between the different treatments, except for the fourth fruit cluster. During the AW season, the chlorophyll contents of functional leaves under the MgF, MgSF, MgSFT, and T treatments were significantly higher than those under the MgS and CK treatments; the T treatment significantly increased the chlorophyll content by 29.2% in the third functional leaves compared with the CK treatment, while the MgSFT 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 MgSF treatment. During the AW season, it was found that the chlorophyll contents were higher under the Mg spray treatments (MgF, MgSF, and MgSFT) than those under other treatments, and those of the soil warming treatments were higher than those under the non-warming treatments.

| Treatments | Second functional leaves | Third functional leaves | Fourth functional leaves | Fifth functional leaves |
|------------|--------------------------|-------------------------|--------------------------|------------------------|
|            | WS | AW | WS | AW | WS | AW | WS | AW | WS | AW |
| CK         | 1.42±0.253 d             | 1.76±0.043 a           | 1.78±0.033 a           | 1.37±0.067 d           | 1.87±0.044 ab          | 1.81±0.031 b           | 1.69±0.081 a           | 1.61±0.138 a           |
| T          | 1.47±0.064 a             | 1.77±0.062 d           | 1.74±0.081 a           | 1.77±0.2 ab            | 1.97±0.185 ab          | 1.83±0.196 b           | 1.71±0.062 a           | 1.69±0.201 a           |
| MgS        | 1.56±0.234 a             | 1.40±0.016 c           | 1.74±0.18 a            | 1.47±0.075 cd          | 1.94±0.119 ab          | 1.82±0.045 b           | 1.72±0.066 a           | 1.71±0.069 a           |
| MgF        | 1.46±0.121 a             | 1.85±0.051 c           | 1.80±0.055 a           | 1.72±0.082 ab          | 1.67±0.326 b           | 1.82±0.044 b           | 1.74±0.04 a            | 1.67±0.026 a           |
| MgSF       | 1.58±0.147 a             | 1.94±0.071 b           | 1.84±0.269 a           | 1.61±0.074 bc          | 1.96±0.299 ab          | 1.96±0.102 ab          | 1.78±0.173 a           | 1.73±0.081 a           |
| MgSFT      | 1.57±0.246 a             | 2.04±0.026 a           | 1.91±0.275 a           | 1.83±0.029 a           | 2.11±0.147 a           | 2.02±0.055 a           | 1.83±0.195 a           | 1.80±0.116 a           |

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

Table 3
The chlorophyll contents of functional leaves in different treatments of Mg fertilizers application (mg g$^{-1}$)
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 CK 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 (T and MgSFT) was lower than that under the CK 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)

| Treatments | N  | P  | K  | Mg |
|------------|----|----|----|----|
|            | WS | AW | WS | AW | WS | AW | WS | AW |
| CK         | 6.18 | 4.78 | 1.48 | 1.22 | 9.84 | 9.02 | 0.43 | 0.19 |
| T          | 6.28 | 6.29 | 1.50 | 1.40 | 7.65 | 10.15 | 0.48 | 0.23 |
| MgS        | 6.56 | 5.13 | 1.44 | 1.06 | 10.09 | 9.62 | 0.43 | 0.22 |
| MgF        | 7.48 | 5.75 | 1.67 | 1.48 | 10.23 | 9.68 | 0.50 | 0.24 |
| MgSF       | 7.55 | 6.40 | 1.84 | 1.59 | 12.11 | 9.91 | 0.53 | 0.24 |
| MgSFT      | 7.56 | 6.28 | 1.55 | 1.33 | 8.23 | 9.91 | 0.60 | 0.25 |

The Mg uptake by tomato plants under Mg fertilizer application treatments was higher than that under the CK 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 MgS and CK treatments during the WS season and the MgSF and 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 (MgF, MgSF, and MgSFT) 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.

Effects of different treatments on tomato yield

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

| Treatments | WS     | AW     | Total of two seasons |
|------------|--------|--------|----------------------|
| CK         | 84.3±2.9c | 103.5±3.2c | 187.8±6.0c          |
| T          | 86.9±2.5c | 116.2±2.3b  | 203.2±4.0 b         |
| MgS        | 87.0±1.2c | 117.2±6.1b  | 204.1±5.2b          |
| MgF        | 91.0±1.1b | 120.4±2.0ab | 211.5±2.7b          |
| MgSF       | 93.0±1.7b | 116.0±2.3b  | 209.0±3.7b          |
| MgSFT      | 97.3±3.3a | 123.5±3.4a  | 220.9±6.4a          |

Different letters in the same column mean significant differences between different treatments at \( P < 0.05 \).

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, 15, 16]. 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% [17]. In this study, the leaf Mg concentration under the CK 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 tomato plants, increase the chlorophyll and Mg contents in leaves, and thus increase tomato yield [18–20]. In this experiment, the three Mg spray treatments (MgF, MgSF, and MgSFT) all had a significant effect; the chlorophyll and Mg contents in leaves, Mg absorbed by tomatoes, and tomato yield were all higher than those under CK. Among the three, MgSFT 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. [21], 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.

However, under the soil application of Mg treatment, the tomato yield was close to that under CK, and the yield increase was lower than that under the Mg spray treatment (Table 5). In this experiment, 150 kg hm\(^{-1}\) of MgSO\(_4\) was applied to soil, which was the same amount used in the experiment conducted by Li et al. in Shijiazhuang [22]; 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. [22], 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, 19]. According to a study by Li et al. [19], 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. Therefore, in this experiment, the observed results may be due to the relatively high content of K in soil, and the amount of Mg applied had not yet reached the ideal K/Mg ratio in the soil, resulting in the Mg soil application not achieving a significant effect.

Temperature affects Mg absorption by tomatoes [8, 23]. The normal temperature for tomatoes to grow and develop 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 (Fig. 2). Compared with the CK 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 [24–26]. 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 [27, 28]. 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, 29, 30]. In addition, soil warming can also increase yield (Table 5), and thus is a recommended treatment for this purpose.

Conclusions

Mg fertilizer application can improve Mg absorption by greenhouse tomatoes. The combination of foliar spray and soil warming showed the highest increase in Mg content and uptake of functional leaves during both the WS and AW seasons. In addition, Mg fertilizer application and soil warming also improved tomato yields, and the combination of foliar spray and soil warming treatment showed the best effect compared with the control. Therefore, foliar spraying of Mg fertilizer and soil warming are two reasonable ways to reduce Mg deficiency in tomato production.

Abbreviations

Mg: Magnesium; CK: armer conventional fertilization practice; MgS: CK + soil application of Mg fertilizer; MgF: CK + foliar spray of Mg fertilizer; MgSF: CK + the combination of soil and foliar spray of Mg fertilizer; T: CK + soil warming; MgSFT: MgSF + soil warming; P2O5: phosphoric anhydride phosphorus pentaoxide; K2O: potassium oxide; WS: winter-spring; AW: autumn-winter; N: nitrogen; P: phosphorus; K: potassium.

Declarations

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Authors' contribution

J.L. and S.J. contributed to the conceptualization. L.M. worked in the methodology. L.M. and S.J. analyzed data. L.M., S.J., and W.Z. wrote the original manuscript. S.J., W.Z., Q.C., X.S. and J.L. reviewed and revised manuscript. S.J., H.S., Y.W. and W.Z. prepared all the figures in the manuscript. J.L. provided funding.

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Availability of data and materials

All data are presented in Tables 1-5 and Fig. 1-2.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.
Competing interests

The authors have no conflict of interest.

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**Figures**
Air temperature at 1 m above the ground measured at 8:30-10:00 am in tomato greenhouse (a). Soil temperature at a depth of 20 cm measured at 8:30-10:00 am in tomato greenhouse (b).
Figure 2

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