Critical Leaf Magnesium Concentrations for Adequate Photosynthetic Production of Soilless Cultured Cherry Tomato—Interaction with Potassium

Xilin Guan 1, Dunyi Liu 2,3, Bin Liu 2,3, Changchun Wu 1, Chuanyun Liu 1, Xiaozhong Wang 2,3, Chunqin Zou 1* and Xinping Chen 2,3*

1 Key Lab of Plant-Soil Interaction, MOE, College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China; guanxilin1102@163.com (X.G.); wucc0377@163.com (C.W.); liuchy2020@163.com (C.L.); zcq0206@cau.edu.cn (C.Z.)
2 College of Resources and Environmental Sciences, Southwest University, Chongqing 400715, China; liudy1989@swu.edu.cn (D.L.); liubin891015@163.com (B.L.); wxz20181707@swu.edu.cn (X.W.)
3 Interdisciplinary Research Center for Agriculture Green Development in the Yangtze River Basin, Southwest University, Chongqing 400715, China

* Correspondence: chenxp2017@swu.edu.cn; Tel: +86-023-68251082

Abstract: Magnesium (Mg) is essential to many plant physiological and biochemical processes; however, understanding how Mg nutrition quantitatively affects the production, partitioning, and utilization of photoassimilates is still lacking, especially in soilless culture systems. We focused on the roles of Mg in yield formation and interactions with potassium (K) nutrition of cherry tomato. Cherry tomato yield, photosynthetic parameters, dry matter weight, and K, Mg, and calcium (Ca) uptake were investigated in two soilless experiments with seven Mg levels and five K levels. The results showed that low (<1 mM) and high (>4 mM) Mg supply limited cherry tomato yield by decreasing dry matter accumulation by 22.6–78.1% and harvest index by 13.9–40.7%. The critical leaf Mg concentrations required for adequate photosynthate production in the first and second harvest periods were 4.67 and 5.52 g·kg⁻¹, respectively. However, over-supply of Mg reduced leaf K and Ca concentrations and limited plant uptake of K and Ca. Moreover, adjusting K concentrations in solution could influence plant Mg functions in photosynthesis and, therefore, cherry tomato growth. Overall, balanced Mg and K application increased Mg, K, and Ca uptake, as well as Mg concentrations in leaves, which could maintain a sustainable photosynthetic rate and plant dry matter formation.

Keywords: magnesium nutrition; Solanum lycopersicum L. yield; critical leaf Mg concentration; photosynthetic rate

1. Introduction

Greenhouse-based vegetable crop production has expanded considerably in recent decades [1,2]. Greenhouse soilless culture facilitates high-yield and high-quality vegetable production by controlling growth environment factors such as temperature, light, and nutrients; among these factors, balanced nutrient supply is particularly important [3–6]. On the other hand, obvious symptoms of Mg deficiency frequently occur in such a system, especially in rapid-growth stages due to imbalanced fertilization or an unfavorable root environment, which causes negative impacts on vegetable yield and quality [7–9]. Therefore, it is imperative to enhance Mg supply for optimal plant physiological functions in this system.

Ensuring sufficient biomass and increasing the harvest index (HI, the ratio of fruit dry matter weight to total plant dry matter weight) of crops at the key growth stages are two effective methods
for obtaining high yield. Mg is a structural component of chlorophyll and a key element in its biosynthesis; thus, Mg is crucial for the production, partitioning, and utilization of photoassimilates in plants [10–13]. Previous studies reported an initial decrease in chlorophyll concentrations in sugar beets affected by Mg deficiency [14] and reduced net CO$_2$ assimilation rates and plant growth as a later response [15,16]. Several studies have investigated the relationship between Mg nutrition and photoassimilate partitioning. The total fruit yield of tomato and the biomass allocated to fruit decreased as the concentrations of supplied Mg were reduced under the rock wool cultivation system [17]. The glucose, Mg content, and dry matter weight of tomato fruit were higher in tomatoes grown in a soilless system supplied with Mg compared to those grown without Mg supply [18]. All of these results indicate that Mg management can help to ensure plant growth by maintaining sufficient biomass generation and HI levels. Therefore, quantitative analyses of leaf Mg concentration with chlorophyll concentration, photosynthetic rate, and plant dry matter should be well performed, especially in soilless systems, which are more sensitive to Mg supply concentration.

Both Mg deficiency and oversupply have detrimental effects on plant growth [19]. Previous studies mainly focused on Mg deficiency and interactions with other cations, e.g., calcium (Ca) and K [20,21]. It was reported that the Mg uptake, transport, and re-translocation were influenced by the availability of K and Ca [10,20]. However, fewer studies emphasized the effects of Mg oversupply. Guo et al. (2015) found that high levels of Mg concentrations in soil solution (>8.5 mM) could obstruct the growth and development of the plant [19]. Photosynthesis impairment has been associated with inhibition of K transport from the cytosol to the stroma and possibly interference of Mg homeostasis within the chloroplast [10,20]. However, the effects of high solution Mg concentrations on K and Ca uptake, leaf chlorophyll content, and photosynthetic rate were not well explored previously.

Mg deficiency should be targeted because its symptoms are more common in high-productivity agriculture [21]. There are two possible reasons which may induce Mg deficiency: absolute short supply and competition with other cations [22]. Absolute deficiency can be accentuated by addition of N, P, and K fertilizers without simultaneous Mg fertilizers, especially in soilless culture systems, which employ a root growth medium containing low nutrient concentrations [23]. Plant Mg uptake is strongly influenced by the availability of other cations such as ammonium, sodium, Ca, and K; among these, K is absorbed to the greatest extent in tomato plants and is essential for high-quality fruit production [24–26]. Unspecific Mg transporters for its uptake can be blocked by high plant available K concentrations in the rhizosphere [20]. However, synergistic effects were noticed between K$^+$ and Mg$^{2+}$ ions in rice plants [21]. Thus, Mg and K supplies can be optimized to enhance crop production under soilless cultivation, and these relationships should be urgently understood for better fruit vegetable production.

Cherry tomato (Solanum lycopersicum L.) consumption has increased dramatically in recent decades, due to its delicate taste, succulent texture, and health-promoting components which may contribute to the prevention of some major chronic diseases [27]. However, nutrient imbalance, especially Mg deficiency, is common under soilless culture systems, where cherry tomatoes are frequently grown [3,7,8]. We hypothesize that the chlorophyll content, photosynthesis characteristics, and nutrient interactions of cherry tomato can be optimized to obtain high yield by regulating nutrient solution Mg levels and, thus, tomato plant Mg content at crucial stages. The overall objectives of this study were (1) to understand the role of Mg in yield formation and dry matter distribution in cherry tomato and clarify the critical leaf Mg level on the basis of chlorophyll content (SPAD reading), photosynthesis characteristics, and plant dry weight (DW), (2) to study Mg surplus effects on K and Ca uptake and photosynthesis, and (3) to compare cherry tomato yield and biomass with different K concentrations in nutrient solution and coordinate K and Mg supply under substrate cultivation.
2. Materials and Methods

2.1. Experimental Setup

Two experiments were conducted under greenhouse conditions from March to July 2016 and March to August 2017 at China Agricultural University (40°02′ north (N), 116°17′ east (E)). Cherry tomato (Solanum lycopersicum L. cv. Qianxi) seeds were procured from Shandong Nongyou Seeds Co., Ltd., Weifang, China. Seeds were sown in 50-cell plug trays filled with a commercial substrate and were germinated and grown in a temperature-controlled chamber (the daylight conditions comprised a 12.5/8 h light/dark cycle with an average temperature of 23.2 °C and 18.8 °C during the day and night, respectively). One month after sowing, the cherry tomato plants with four fully unfolded true leaves were transplanted into a growth medium consist of coconut coir at a planting density of 40,000 plants ha⁻¹. The available K, Ca, and Mg contents and the cation exchange capacity of coconut coir were 0.50%, 0.30%, 0.13%, and 683 mmol·kg⁻¹. Daily temperatures in the greenhouse was recorded every 2 h by an automatic temperature recorder (DS1922L, produced by Wdsen Electronic Technology Co., Ltd., Shanghai, China), as shown in Figure S1 (Supplementary Materials).

In the Mg experiment, cherry tomato plants were fertilized with seven Mg treatments (0, 0.5, 1, 2, 4, 8, and 16 mM) together with 12 mM K supplied in nutrient solution. In the K experiment, taking the results of the Mg experiment into account, we applied five levels of K (7, 12, 17, 22, and 27 mM) and 2 mM Mg in nutrient solution. The Mg or K molar concentration was calculated using the following formula: \( c = \frac{m}{MV} \), where \( c \) is the concentration of \( \text{Mg}^{2+} \) or \( \text{K}^{+} \) in the solution (mM), \( m \) is the mass of Mg or K (mg), \( M \) is the molar mass of Mg or K (g·mmol⁻¹), and \( V \) is the volume of the solution (L). The magnesium sulfate and potassium nitrate were dissolved in deionized water. The cherry tomato plants were transplanted on 20 April 2016 and 26 April 2017 in the Mg and K experiments, respectively. In both experiments, the experimental design was a randomized block design with three replications. Two side rows were planted as guard rows in each experiment; thus, we planted a total of nine and seven plant rows for the Mg and K experiments, respectively, and there were 15 plants in each row. In all treatments, we supplied 240 mg·L⁻¹ N and 35 mg·L⁻¹ P during the seedling and anthesis periods in all treatments, while 230 mg·L⁻¹ N and 22 mg·L⁻¹ P were supplied during the fruit stage. We supplied 90 mg·L⁻¹ Ca, 6.4 mg·L⁻¹ iron (Fe), 0.8 mg·L⁻¹ manganese (Mn), 0.2 mg·L⁻¹ zinc (Zn), 0.1 mg·L⁻¹ copper (Cu), and 0.5 mg·L⁻¹ boron (B) during every irrigation period, and we adjusted the pH to 5.5–7.0 using nitric acid (HNO₃) or sodium hydroxide (NaOH) every 2 days. Each treatment had an independent fertigation system controlled by an electromagnetic relay. The fertigation frequency worked, and the plants were watered up with solutions containing different amounts of K or Mg. Flow-through water was collected and poured once again to recycle the solution in the closed system. During the whole growth period, some measures (e.g., a hanging yellow sticky trap) were adopted to prevent plant diseases and insect pests.

2.2. Leaf and Plant Measurements

At anthesis (about 30 days after transplanting, one or two bunches of flowers blooming), first harvest period (about 60–70 days after transplanting, two to four bunches of fruits maturing), and second harvest period (about 85–103 days after transplanting, four to six bunches of fruits maturing), the roots, stems, leaves, and fruits of the cherry tomato plants were harvested. Total fresh fruit yield and marketable fruit yield (single fruit weight >15 g; no damage) were recorded at every harvest. Plant samples were washed with tap water and deionized water, and then dried at 75 °C to constant weight. Dry samples were ground using a stainless-steel grinder for K, Ca, and Mg analyses. A certain amount of samples (0.3 g) were digested with HNO₃–H₂O₂ (6 mL of HNO₃ and 2 mL of H₂O₂) in a microwave-accelerated reaction system (CEM, Matthews, NC, USA), and the K, Ca, and Mg concentrations in the digesting solutions were determined by inductively coupled plasma optical emission spectroscopy (ICP-OES, OPTIMA 3300 DV, Perkin-Elmer, Waltham, MA, USA).
Standard materials for K, Ca, and Mg analyses (IPE126) were obtained from Wageningen Evaluation Programs for Analytical Laboratories (WEPAL, Naaldwijk, The Netherlands).

In the Mg experiment, we randomly selected one middle leaf from the fourth branch on plant in each repetition in the morning (09:00 a.m.–12:00 p.m.) to measure photosynthetic rate using a portable photosynthesis apparatus (LCpro-SD; ADC BioScientific Ltd., Hoddesdon, UK) under natural sunlight conditions with a light intensity of 500–800 µmol·m⁻²·s⁻¹ and circumambient CO₂ concentration of 340–370 µM. The SPAD readings were taken with a chlorophyll meter (SPAD-502, Minolta, Tokyo, Japan), measurements were conducted in the middle leaf of the third or fourth branch from tip on plant, and the mean of six values was taken as the final result for each repetition. This procedure was followed at anthesis and repeated during the first and second harvests.

2.3. Statistical Analysis

SAS v. 8.0 (SAS, Cary, NC, USA) and SPSS v. 20.0 (SPSS, Chicago, IL, USA) software was used for statistical analyses. Means were compared using analysis of variance (ANOVA), followed by Duncan’s multiple range test at a significance level of \( p < 0.05 \). The responses of SPAD, photosynthetic rate, and plant dry matter to leaf Mg concentration were described using the linear-with-plateau model.

3. Results

3.1. Fruit Yield, Biomass, and HI Were Affected by Mg Treatment Concentration

With increasing Mg concentrations in nutrient solution, the cherry tomato fruit yields increased to 293 and 425 g·plant⁻¹ in the first and second harvest periods, respectively, and then decreased (Table 1). In both harvest periods, the fruit yields in the 1–4 mM Mg treatments were significantly higher than those in the 0, 0.5, and 16 mM Mg treatments (Table 1). In the first harvest period, cherry tomato yields and plant DWs did not differ significantly among the 1–8 mM Mg treatments, but were affected at very low (<1 mM) or high (>8 mM) Mg levels. By contrast, in the second harvest period, cherry tomato yields and plant DWs were more sensitive at higher Mg treatment concentrations (Table 1).

| Mg Concentration in Solution (mM) | Yield (g Plant⁻¹ FW) | Plant Dry Weight (g Plant⁻¹) | Harvest Index (%) |
|-----------------------------------|----------------------|------------------------------|-------------------|
|                                   | First Harvest        | Second Harvest               | First Harvest     | Second Harvest | First Harvest | Second Harvest |
| 0                                 | 29c†                 | 67d                          | 16.8e             | 16.8d          | 21.9b         | 31.2c          |
| 0.5                               | 172b                 | 187c                         | 50.6d             | 59.7c          | 26.3a         | 24.4d          |
| 1                                 | 290a                 | 398a                         | 66.2ab            | 75.5ab         | 27.9a         | 41.1a          |
| 2                                 | 281a                 | 425a                         | 63.2b             | 76.5ab         | 26.1a         | 42.7a          |
| 4                                 | 293a                 | 397a                         | 65.3ab            | 78.2a          | 26.9a         | 39.6ab         |
| 8                                 | 284a                 | 335b                         | 67.2a             | 73.8b          | 27.3a         | 35.4bc         |
| 16                                | 152b                 | 162c                         | 57.4c             | 59.4c          | 17.7c         | 21.3d          |

† Values are the means of three replications. Means in each column followed by the same letters are not significantly different at \( p < 0.05 \) according to Duncan’s multiple range test.

HI values were 17.7–27.9% and 21.3–42.7% at first and second harvest, respectively, and were lowest for the Mg treatment of 16 mM in both periods (Table 1). The HI at the second harvest period was more affected by Mg concentrations in solution than that at the first harvest period. Higher HI (39.6–42.7%) was observed for the 1–4 mM solution Mg supply at the second harvest period, but the lower (<1 mM) or higher (>4 mM) Mg supply decreased HI by 24.4–31.2% and 21.3–35.4%, respectively (Table 1).
3.2. Leaf Mg Concentration Regulated Leaf Chlorophyll, Photosynthetic Rate, and Plant DW

Low concentrations of Mg in nutrient solution significantly reduced Mg concentrations in leaves, especially at the later growth stage (Table 2). Cherry tomato plants showed the typical symptom of Mg deficiency with Mg concentration in solution below 1 mM, including leaf yellowing in the form of interval chlorosis in older leaves in early anthesis, slow growth, and small fruits at the harvest period. Compared with the 1 mM Mg treatment, the 0 mM Mg treatment decreased the leaf Mg concentrations by 17.9%, 26.8%, and 31.7% at anthesis, first harvest, and second harvest, respectively (Table 2). The leaves of plants supplied with low levels of Mg had a significantly lower SPAD reading; thus, net photosynthetic rates were also lower in the lower Mg treatments (Table 2).

### Table 2. Leaf Mg concentrations, SPAD readings, and net photosynthetic rates of cherry tomato plants under different nutrient solution Mg concentrations at anthesis and the first and second harvest periods.

| Mg Concentration in Solution (mM) | Leaf Mg Concentration (g kg⁻¹) | SPAD Reading | Photosynthetic Rate (µmol CO₂ m⁻² s⁻¹) |
|-----------------------------------|--------------------------------|--------------|----------------------------------------|
|                                   | Anthesis | First Harvest | Second Harvest | Anthesis | First Harvest | Second Harvest | Anthesis | First Harvest | Second Harvest |
| 0                                 | 3.66d    | 3.31f         | 3.25e         | 32.6b    | 26.0d         | 19.3e         | 7.2d      | 4.5d          | 3.4c          |
| 0.5                               | 3.73d    | 3.40f         | 3.58e         | 46.3a    | 40.4c         | 34.5d         | 10.6c     | 7.2c          | 4.7b          |
| 1                                 | 4.46cd   | 4.52e         | 4.76de        | 46.3a    | 44.6b         | 41.2c         | 14.1b     | 14.4a         | 12.2a         |
| 2                                 | 4.46cd   | 7.33d         | 6.39d         | 44.1a    | 45.6ab        | 47.0b         | 15.5b     | 14.0a         | 13.1a         |
| 4                                 | 4.90c    | 9.57c         | 10.3c         | 43.4a    | 46.1ab        | 48.8a         | 17.8a     | 13.5a         | 12.7a         |
| 8                                 | 6.89b    | 13.2b         | 14.5b         | 44.3a    | 47.0a         | 49.7a         | 18.0a     | 12.9a         | 12.5a         |
| 16                                | 7.95a    | 16.6a         | 17.0a         | 46.1a    | 47.4a         | 48.6ab        | 19.1a     | 8.9b          | 11.9a         |

† Values are the means of three replications. Means in each column followed by the same letters are not significantly different at \( p < 0.05 \) according to Duncan’s multiple range test.

A linear-with-plateau model produced the best fit for the relationships between SPAD reading and photosynthesis rate against leaf Mg concentration at the first and second harvest; however, the model did not fit at the anthesis stage (Figure 1a–f). As indicated by the plateau, SPAD readings and photosynthetic rates were highest at leaf Mg concentrations of 4.67 and 4.41 g·kg⁻¹ at first harvest and 5.52 and 5.01 g·kg⁻¹ at second harvest (Figure 1a–f). Mg nutrition improved plant DW both at anthesis and at the first and second harvest, and it increased to 15.4 g·plant⁻¹, 64.4 g·plant⁻¹, and 76.6 g·plant⁻¹ in these three growth stages before plateauing (Figure 1g–i). The critical leaf Mg concentration for high plant DW was about 4.41, 4.38, and 4.50 g·kg⁻¹ at these three growth stages, which was lower than that for the high SPAD reading and photosynthetic rate (Figure 1a–i).

3.3. Oversupply of Mg Reduced Leaf K and Ca Levels, and Limited Plant K and Ca Uptake

Leaf K and Ca levels were affected by Mg supply. In the low-Mg treatment (<1 mM), the K and Ca concentrations in leaves decreased as Mg supply increased (Table 3). Compared with the 1 mM solution Mg treatment, the leaf K and Ca levels decreased from 43.4 to 30.0 g·kg⁻¹ and 17.8 to 11.5 g·kg⁻¹ in the 16 mM treatment (Table 3). However, fruit Ca concentration was disturbed by Mg supply levels to a greater extent than K, and it significantly decreased when Mg concentration in solution exceeded 2 mM (Table 3).

Plant DWs were slightly lower in the 16 mM Mg treatment than in the 4 mM treatment at first and second harvest (Table 1). Plant nutrient uptakes are determined by plant DWs and nutrient concentrations. Therefore, plant Mg, K and Ca uptakes showed different trends. The uptakes of K and Ca first increased before reaching 1 mM with the Mg treatment level and then decreased. In contrast, plant Mg uptake increased significantly as nutrient solution Mg concentration increased (Table 3).
3.4. Potassium Supply Affected Leaf K and Mg Levels, in Turn Affecting Plant DW, Mg Uptake, and Fruit Yield

K supply determined leaf K and Mg concentrations (Figure 2a,b). In the K experiment, leaf Mg concentration decreased when solution K concentration increased, and leaf Mg concentration was below 4.67 mg·kg\(^{-1}\) when solution K concentration exceeded 17 mM (Figure 2). However, leaf K concentration showed the opposite trend, with levels below 38.0 mg·kg\(^{-1}\) when solution K concentration was less than 12 mM (Figure 2).
Generally, higher plant DWs were obtained at 12–22 mM K concentrations in nutrient solution (Table 4). It first increased with leaf K concentration before reaching a maximum at 17 mM K supply, which was 17% higher than that of the 7 mM K supply treatment. In contrast, plant DW increased with increasing leaf Mg concentrations (Figure 2c,d). Generally, higher plant DWs were obtained at 12–22 mM K concentrations in nutrient solution (Figure 2c,d).

The plant DW of cherry tomato was 92.6 g plant\(^{-1}\) at 12 mM K supply, which was 17% higher than that of the 7 mM K supply treatment. It first increased with leaf K concentration before reaching 41.9 g kg\(^{-1}\) and then decreased. In contrast, plant DW increased with increasing leaf Mg concentrations (Figure 2c,d). Generally, higher plant DWs were obtained at 12–22 mM K concentrations in nutrient solution (Table 4).

Table 4. Yield (fresh weight, FW), marketable fruit rate (MFR), plant dry weight (DW), and harvest index (HI) of cherry tomato in response to different K concentrations supplied in nutrient solution at the second harvest period.

| K Concentrations in Solution (mM) | 7   | 12  | 17  | 22  | 27  |
|----------------------------------|-----|-----|-----|-----|-----|
| Cherry tomato fruit †            | ![Image](image.png) |
| Yield (g plant\(^{-1}\) FW)      | 552ab | 579a | 499bc | 493c | 463c |
| MFR (%)                          | 86.1b | 92.4a | 87.0b | 85.6b | 84.9b |
| Plant DW (g plant\(^{-1}\))      | 79.3b | 92.6a | 84.3ab | 85.4ab | 77.2b |
| HI (%)                           | 54.1a | 48.6b | 46.0b | 44.9b | 46.6b |

† The photograph was captured in the second harvest period. The upper and lower fruits in the photograph refer to marketable fruits and nonmarketable fruits, respectively. Values are the means of three replicate pots. Means in each line followed by the same letters are not significantly different at \(p < 0.05\) according to Duncan’s multiple range test.
The total yield of cherry tomato was highest when K concentration in solution was 12 mM. The marketable fruit rate decreased from 92.4% to 84.9% as K supply varied from 7 to 27 mM (Table 4). Thus, K supply levels regulated plant DW via leaf K and Mg concentrations, subsequently influencing cherry tomato yield and Mg, K, and Ca uptake (Table 4; Figure S2, Supplementary Materials).

4. Discussion

4.1. Mg Application Affected Photosynthetic Production and Distribution

Cherry tomato yield and dry matter accumulation were significantly affected by solution Mg concentration, which is consistent with the findings of Nzanza (2006) [28]. Increased yield and dry matter accumulation in response to proper Mg application were also observed by Hao and Papadopoulos (2003), who reported decreased fruit yield in the late growth stage at 0.82 mM solution Mg supply in rockwool blocks [4]. Moreover, in later studies, Hao and Papadopoulos (2004) explained this as being the result of a decrease in biomass and fruit biomass allocation in the low-Mg treatment [17]. We observed that lower plant DW and HI reduced yield in response to low-Mg application (<1 mM). The different water-holding capability and buffer ability of growth media were the main reasons for the difference since the marketable yield was also affected by the soilless culture system [29].

The photosynthetic rates of the cherry tomato plants decreased significantly in the 0 and 0.5 mM treatments. A previous study reported that the middle and bottom leaves of cherry tomato plants grown in a soilless production system showed leaf chlorosis under Mg starvation, losing about 50% of their photosynthetic capacity [4]. Impairment of sugar metabolism, photosynthetic CO$_2$ fixation, and stomatal conductance were reported by Cakmak et al. (1994) and Fischer et al. (1998) in bean and spinach plants [30,31], and Andersson (2008) demonstrated that the involvement of rubisco in CO$_2$ fixation was adversely affected by poor Mg supply [32].

The decrease in HI among cherry tomato plants observed under lower Mg supply in this study indicates the suppression of assimilate distribution to fruits. Sugar accumulation in source organs and the decline of its distribution to sink tissues were reported previously. Hermans et al. (2004) found that sucrose accumulated in the most recently expanded sugar beet leaves before any loss of photosynthetic activity under Mg deficiency treatment [14]. Farhat et al. (2016) attributed this to preference of Mg transported to source leaves to prevent severe declines in photosynthetic activity [21]. Mg starvation seems to have a direct detrimental effect on function and/or structure of phloem loading [21,30,33,34].

4.2. Relationships among Leaf SPAD Reading, Photosynthetic Rate, Plant DW, and Leaf Mg Concentration

Leaf Mg concentrations increased continuously as solution Mg levels increased in this study. A former study of Sulla carnosa plants also showed increased leaf Mg concentrations, to 2.5-, 7-, and 25-fold that of the control (0 mM Mg treatment) in 0.01, 0.05, and 1.50 mM Mg treatments, respectively [12]. In this study, the linear-with-plateau model illustrated the relationship between SPAD reading and leaf Mg concentration at the first and second harvests, and the critical leaf Mg concentrations for SPAD reading were about 4.67 and 5.52 g·kg$^{-1}$ in these periods. The SPAD reading is an indicator of leaf chlorophyll concentration, which determines photosynthetic rate to a great extent [21]. Therefore, photosynthesis rates also fitted this model, and the critical leaf Mg concentrations for photosynthesis rates were 4.41 and 5.01 g·kg$^{-1}$ at the first and second harvests. A previous report indicated that maintenance of normal plant growth required 4.0–6.0 g·kg$^{-1}$ leaf Mg concentration in tomato plants at anthesis, and the marginal concentration in the first harvest period was 3.0 g·kg$^{-1}$ [35]. The linear-with-plateau model was also applied to dry matter formation, and the critical leaf Mg concentrations were 4.38 and 4.50 g·kg$^{-1}$ at the first and second harvests, slightly lower than those for the photosynthesis rate. Similarly, dry matter accumulation in Pinus radiata was shown to be inhibited by Mg deficiency [36]. Hauer-Jäkli and Tränkner (2019) confirmed 3.9 g·kg$^{-1}$ as the critical leaf Mg concentration for tomato dry matter accumulation on the basis of the results of Kasinath et al. (2014) using the scattered plot technique, which was lower than this study [16,37] (Table S1, Supplementary Materials).
The different critical leaf Mg concentrations with respect to SPAD reading, photosynthesis rate, and plant dry matter accumulation indicated that sufficient Mg supply can guarantee the chlorophyll concentration and the production of photosynthates. The result was consistent with a study showing that plant growth reduction appeared as a later response compared with chlorophyll content decrease caused by Mg deficiency [15]. Clear relationships were observed between SPAD reading, photosynthesis rate, plant dry matter accumulation, and leaf Mg concentration. These relationships may be explained by the adequate Mg supply during initial growth stages [16]. The results above clearly demonstrate the importance of Mg supply in maintaining strong photosynthesis to produce cherry tomato dry matter.

4.3. Two Side Effects of Mg Application on the Plant K and Ca Content

In the second harvest period, the plant K and Ca uptakes of cherry tomato first increased with Mg concentration in solution lower than 1 mM and then decreased, as indicated by the plant dry matter accumulation and the leaf K and Ca concentration.

The plant dry matter accumulation increased first with Mg concentrations in solution increasing but decreased for Mg treatment concentrations over 8 mM and 4 mM at the first and second harvest periods. The positive effects of Mg nutrient supply on plant growth have been discussed extensively [16,36,38]. The inhibitive effects observed in this study have rarely been reported due to the difficulty in detecting toxicity symptoms, even at high concentrations [39]. The inhibitive effect of high Mg supply on plant dry matter accumulation was caused by slight decreases in the photosynthetic rate at first and second harvest. A similar effect was observed by Rao et al. (1987), who found that net photosynthesis was inhibited to a much greater extent in sunflower plants with a high Mg$^{2+}$ content, particularly during dehydration [40]. Moreover, Shaul (2002) and Koch et al. (2019) associated this decrease with K$^+$ transport inhibition from the cytosol to the stroma, disequilibrium within the chloroplast, and interference in transport events across the tonoplast [10,20]. Mun et al. (2020) explained the deleterious effects of Mg oversupply on Perilla frutescens growth and yield as the decrease in relative abundance of bioactive phytochemicals, such as triterpenoids, flavonoids, and cinnamic acids [41].

Low leaf K and Ca levels with high Mg supply treatments indicate antagonistic effects among these cations [26]. When solution Mg concentration was higher than 4 mM, the leaf K concentration was lower than 38.0 g·kg$^{-1}$, which might induce K deficiency [35,42]. Leaf Ca concentration also decreased in higher Mg supply treatments, but was higher than 10 g·kg$^{-1}$ [35]. The response of fruit Ca concentration was more sensitive than that of K to Mg concentrations in this study, consistent with the results of Marschner (2012), who reported sevenfold higher K distribution than Ca distribution in pea seeds [26], while Karley and White (2009) also noticed this phenomenon [43].

4.4. K Application Influenced Cherry Tomato Growth by Regulating Plant Mg and K

Antagonistic effects of K on Mg, especially under inadequate Mg supply conditions, are a crucial factor influencing Mg-related functions in several crops, including tomato [42,44], green bean [45], potato [46], rice [47], grape [48], and apple [49]. The present study showed that an increasing K concentration in solution adversely affected the leaf Ca and Mg concentrations. Leaf Mg and Ca concentrations were lower than 4.7 and 10.0 mg·kg$^{-1}$ when solution K concentrations exceeded 17 mM under the 2 mM solution Mg supply, indicating Mg (from the former experiment in this study) and Ca deficiency [35]. However, K deficiency may have occurred when solution K concentration was less than 12 mM because leaf K concentration was lower than 38.0 mg·kg$^{-1}$ [35,42]. These findings may explain the influence of K supply levels on total yields and plant DWs. This result was in line with Yurteşen et al. (2005) and Sonntag et al. (2019), who reported that significant yield increases with increasing K application [50,51]. However, Nzanza (2006) found that none of the applied K treatments had any significant effect on marketable tomato yield [28]. The difference could be explained by the maximum K supply concentration, 9 mM in the study reported by Nzanza (2006) and 27 mM in this
study [28]. Moreover, the different growth media used in the studies may also have been responsible for the difference.

Leaf K, Ca, and Mg concentrations are regulated by the K concentration in solution, as well as plant K, Ca, and Mg uptake. Ali et al. (1991) found that K, Ca, and Mg leaf contents in tomato decreased to 38%, 45%, and 67% of that of control plants under low K, low Ca, and low Mg supply, respectively, and that leaf, stem, and petiole dry matter also decreased significantly [52]. Another study reported that rice shoot DW decreased by 12.9% at high K/Mg ratios in solution, whereas root DW increased by 12.1% as sugar partitioning and root morphological parameters changed [53]. Toumi et al. (2016) also reported that Mg uptake was inhibited by an increase in K/Mg in the nutrient solution in *Vitis vinifera*, but no significant differences in leaf Ca concentration were detected among treatments [48].

4.5. Mg and K Management in Soilless Vegetable Production

Since the functions of Mg in the production, partitioning, and utilization of plant photoassimilates are irreplaceable, adequate Mg supply in the rhizosphere is essential for high-productivity soilless vegetable production systems. According to our results, 1–4 mM Mg in solution was needed to ensure leaf Mg concentrations exceeding 4.67 g·kg⁻¹ at the early harvest and 5.52 g·kg⁻¹ at late harvest, which could also satisfy the requirements for optimized SPAD, photosynthesis rate, and plant dry matter accumulation combined with high fruit yield. These leaf Mg concentrations are slightly higher than that reported in previous studies, which demonstrated that tomato dry matter accumulation responded best at 3.9 g·kg⁻¹ plant Mg concentration [37,54]. However, excessive Mg concentrations (>8 mM) in solution should be avoided due to the risk of adverse effects on photosynthesis. Toxic effects that impair crop growth and development were also shown by Guo et al. (2015) when Mg concentration in soil solution was higher than 8.5 mM [19].

Mg deficiency is a common problem in growth media fertilized only with N, P, and K [7,21]. Consequently, harmonious crop-specific nutrient management requires further attention. Overuse of K fertilizer not only wastes K resources but also disturbs Mg uptake and reduces yield [53,55]. Therefore, K concentrations in soilless culture systems should be managed to supply sufficient leaf K to achieve high yield, while avoiding Mg uptake suppression due to excessive K. Moreover, the plant yield and quality are closely related to plant growth media, which could influence the nutrient supply concentrations in solution [29]. Wang et al. (2009) reported that higher yields were obtained when solution K concentration was at 2.5–5 mM for cherry tomato growing in plastic pots filled with sand [56]. Hao and Papadopoulos (2003) applied 10 mM K in the nutrient solution for greenhouse tomato crop grown on rockwool [4]. Constan-Aguilar et al. (2014) observed that cherry tomato fruit dry matter was higher when K concentrations ranged from 10 to 15 mM using perlite as the growth medium [57]. Comparatively, in this study, we used coconut coir as the growth medium, and the results indicate that 12 mM K in solution is optimal in this environment according to our nutrient uptake and photosynthate production results. Therefore, the optimal nutrient concentration in solution is usually higher when using growth media with a higher cation exchange capacity and greater water-holding capability [58]. We also established relationships of leaf K or Mg concentrations with cherry tomato dry matter in this study, which are crucial for understanding the mechanisms of yield formation in soilless vegetable production systems.

5. Conclusions

Inadequate Mg supply impairs yield by influencing production and distribution of photosynthesis products. When Mg supply in solution varied from insufficient to adequate, the SPAD reading, photosynthesis rate, and plant dry matter accumulation of cherry tomato increased first with leaf Mg concentration and then plateaued. As indicated by the plateau, critical leaf Mg concentrations were 4.67 and 5.52 g·kg⁻¹ at the first and second harvest periods, illustrating that sufficient Mg supply was crucial for the proper chlorophyll concentration and the production of photosynthates. Moreover, plant dry matter accumulation was inhibited at high Mg treatment levels as a result of a slight decrease
in the photosynthetic rate in the first and second harvest periods. As a crucial factor influencing functions of Mg, K concentrations in solution influence cherry tomato growth by regulating plant Mg and K uptake. The leaf Mg concentration decreased when solution K concentration increased. Generally, 1–4 mM Mg in solution was needed for cherry tomato to satisfy the requirements for optimized SPAD, photosynthesis rate, and plant dry matter accumulation combined with high fruit yield. Similarly, a K concentration of 12 mM in solution is recommended on the basis of nutrient uptake and photosynthetic production in the substrate cherry tomato cultivation system.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/12/1863/s1:
Figure S1. Mean daily temperatures (recorded every two hours) in the vegetation period during the Mg and K experiments in the greenhouse; Figure S2. Effects of K concentrations in solution on plant potassium (K), calcium (Ca), and magnesium (Mg) uptake by cherry tomato plants; Table S1. Critical leaf Mg concentrations for tomato growth in different substrates; Table S1. Critical leaf Mg concentrations for tomato growth in different substrates.

Author Contributions: Conceptualization, X.G.; formal analysis, X.G. and D.L.; funding acquisition, C.Z.; investigation, B.L., C.W., and C.L.; methodology, X.W.; project administration, X.G.; resources, D.L., C.W. and C.L.; software, X.G. and B.L.; supervision, X.C.; validation, X.G.; visualization, C.Z. and X.C.; writing—original draft, X.G.; writing—review and editing, D.L. and X.C. All authors have read and agreed to the published version of the manuscript.

Funding: The work was supported by the National Key Research and Development Program of China (No. 2017YFD0800403) and the State Cultivation Base of Eco-agriculture for Southwest Mountainous Land (Southwest University).

Acknowledgments: The authors are grateful to the staff at the College of Resources and Environmental Sciences, China Agricultural University, for their assistance with the sample test.

Conflicts of Interest: The authors declare no conflict of interest.

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