Magnesium supply regulate leaf nutrition and plant growth of soilless cultured cherry tomato - interaction with potassium

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Abstract

Background: Magnesium (Mg) is essential to many plant physiological and biochemical processes; however, a quantitative understanding of how Mg nutrition affects the production, partitioning and utilization of photoassimilates is still lacking, especially for soilless culture system. We focused on the roles of Mg in yield formation and interactions with potassium (K) nutrition of cherry tomato. Cherry tomato yield, leaf Mg concentration, 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.

Results: Low (<1 mM) and high (>4 mM) Mg supply limited cherry tomato yield by decreasing 22.6-78.1% dry matter accumulation and 13.9-40.7% harvest index. 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. But over-supply of Mg disturbed leaf K and Ca concentrations, limiting the plant K and Ca content. Moreover, adjusting K concentrations in solution is a crucial factor influencing plant Mg functions, and therefore cherry tomato growth.

Conclusion: Balanced Mg and K application increased Mg, K, and Ca uptake by cherry tomato, as well as Mg concentrations in leaves which could maintain a sustainable photosynthetic rate and plant dry matter formation.

Background

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, nutrient control is the most important [3–6]. Unlike nitrogen, phosphorus and potassium (K), magnesium (Mg) has tended to be a “forgotten element” in crop production [7], especially in soilless fruit vegetable production systems, because the target nutrient concentrations in the nutrient solution is often determined by electric conductance and crop-specific nutrient solutions are applied relative rarely [3, 8]. However, adequate Mg supply is important for optimal plant physiological functions.

Ensuring sufficient biomass and increasing the harvest index (HI, the percent of fruit dry matter weight to total plant dry matter weight) of crops at 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 [9–12]. Previous studies have reported an initial decrease in chlorophyll concentrations in sugar beets affected by Mg deficiency [13] and reduced plant growth as a later response [14]. 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 rook wool cultivation system [15]. The glucose, Mg content and dry-matter weight of tomato fruit were higher in tomatoes grown in a soilless system supplied with Mg [16]. All of these results indicate that Mg

management can help to ensure plant growth by maintaining sufficient biomass generation and HI levels. However, quantitative analyses of leaf Mg concentration with chlorophyll concentration, photosynthetic rate and plant dry matter have not been performed in soilless systems, which are more sensitive to Mg supply concentration.

Both Mg deficiency and oversupply have detrimental effects on plant growth [17]. Guo et al. (2015) found that high levels of Mg concentrations in soil solution (> 8.5 mM) could obstruct the growth and development of plant [17]. 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 [9, 18]. Unfortunately, the effects of high solution Mg concentrations on leaf chlorophyll content and photosynthetic rate, and its interactions with K and calcium (Ca) have not been well explored previously.

In crop production, Mg deficiency is of greater concern than Mg toxicity because its symptoms are more common in high-productivity agriculture [19]. Two aspects of the effects of Mg deficiency on crops have been extensively studied: absolute short supply and competition with other cations [20]. Absolute deficiency can be accentuated by addition of N, P and K fertilizers without simultaneous Mg fertilizers, especially in soilless culture systems, which employ root growth medium containing low nutrient concentrations [21]. 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 to high-quality fruit production [22–24]. Unspecific Mg transporters for Mg uptake can be blocked by high plant available K concentrations in the rhizosphere [18]. Thus, Mg and K antagonism can be managed to enhance crop production under soilless cultivation. However, these relationships remain poorly understood for better fruit vegetable production.

Cherry tomato (Lycopersicon esculentum Mill.) 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 [25]. However, nutrient imbalance, especially Mg deficiency, is common under soilless culture systems, where cherry tomatoes are frequently grown [3, 7, 8]. We hypothesize that 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 to understand the role of Mg in yield formation and dry matter distribution in cherry tomato and clarify the critical leaf Mg level based SPAD reading, photosynthesis characteristics, and plant dry weight (DW); to study Mg surplus effects on photosynthesis and interactions with K and Ca; and to analyse the effects of K and Mg concentrations in nutrient solution on cherry tomato yield and biomass, and coordinate K and Mg supply under substrate cultivation.

Results

Fruit yield, biomass and HI affected by Mg treatment concentration

Cherry tomato fruit yields and plant DWs increased with nutrient solution Mg concentration and then decreased when fruit yields reached 293 and 425 g plant^{-1} in the first and second harvest periods, respectively (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).

Table 1 Nutrient solution Mg concentration effects on yield (fresh weight, FW), plant dry weight, and harvest index in cherry tomato plants.

Mg concentration in solution (mM)	Yield (g plant^{-1} FW)		Plant dry weigh (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 same letters are not significantly different at $P<0.05$ according to Fisher's least significant difference [LSD] test.

HI values were 17.7-27.9% and 21.3-42.7% at first and second harvest, and were lowest for the Mg treatment of 16 mM in both periods (Table 1). Moreover, the HI at the second harvest period was greater affected by Mg concentration in solution, the highest HI was about 41.1% at 1-4 mM solution Mg supply, but the lower (<1 mM) or higher (>4 mM) Mg supply decreased HI to 24.4-31.2% and 21.3-35.4% respectively (Table 1).

Leaf Mg concentration regulated leaf chlorophyll, photosynthetic rate, and plant DW

Low nutrient solution Mg significantly reduced Mg concentrations in leaves, especially in the later growth stage (Table 2). Cherry tomato plants showed the typical symptom of Mg deficiency including interval chlorosis in the early anthesis with Mg concentration in solution below 1 mM. Compared with the 1 mM

Mg treatment, no Mg supply led to reductions in leaf Mg concentrations of 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 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, first and second harvest periods.

Mg concentration in solution (mM)	Leaf Mg concentration (g kg^{-1})			SPAD reading			Photosynthetic rate (μmol CO_2 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 same letters are not significantly different at $P<0.05$ according to Fisher's LSD 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, but the model did not fit at anthesis (Fig. 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 (Fig. 1a–f). Mg nutrition improved plant DW both in the anthesis and 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 those three growth stages and then plateaued (Fig. 1g-i). The critical leaf Mg concentration for high plant DW were about 4.41, 4.38 and 4.50 g kg^{-1} at those three growth stages, which was lower than those for high SPAD reading and photosynthetic rate (Fig. 1a-i).

Oversupply of Mg disturbed leaf K and Ca levels, limiting plant K and Ca content

Leaf K and Ca levels were affected by Mg supply. In the low Mg treatment (<1 mM), the K and Ca concentration in leaves were decreased as Mg supply increased (Table 3). Compared with 1 mM solution Mg treatment, the leaf K and Ca levels were 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 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 contents are determined by plant DWs and nutrient concentrations.

Therefore, plant Mg, K and Ca contents showed different trends. The contents of K and Ca were first increased before reaching 1 mM with the Mg treatment level and then decreased. In contrast, plant Mg content increased significantly as nutrient solution Mg concentration increased (Table 3).

Table 3 Effects of Mg concentration in nutrient solution on leaf and fruit potassium (K), calcium (Ca), and magnesium (Mg) concentrations, and plant Mg, K, and Ca contents in the second harvest period.

Mg concentration in solution (mM)	Leaf nutrient concentration (g kg^{-1})		Fruit nutrient concentration (g kg^{-1})			Plant nutrient content (mg $plant^{-1}$)		
	K	Ca	Mg	K	Ca	Mg	K	Ca
0	35.2b	8.68d	2.39a	48.2b	2.33a	31f	570e	95e
0.5	42.2a	14.4b	2.38a	59.5a	1.80b	135e	2437c	536b
1	43.4a	17.8a	2.39a	55.9ab	1.90b	196d	3229a	591a
2	42.5a	17.0a	2.33a	50.4ab	1.26c	232c	3102ab	515b
4	37.3b	15.3b	2.49a	52.4ab	1.17c	350b	3138ab	521b
8	37.7b	14.2b	2.71a	53.6ab	1.28c	454a	2869b	444c
16	30.0c	11.5c	3.00a	49.5ab	1.03c	456a	1961d	334d

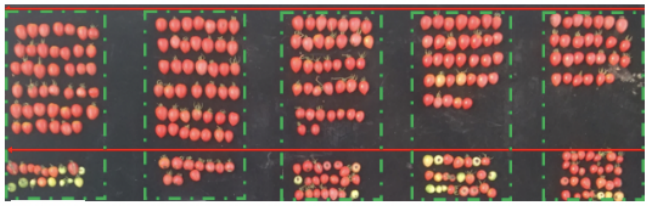
Values are the means of three replications. Means in each column followed by same letters are not significantly different at $P<0.05$ according to Fisher's LSD test.

K supply greatly affected leaf K and Mg levels, in turn affecting plant DW, Mg uptake, and fruit yield.

K supply determined leaf K and Mg concentrations (Fig. 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 (Fig. 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 (Fig. 2).

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. And it was first increased with leaf K concentration before reaching 41.9 g kg^{-1} and then decreased. In contrast, plant DW increased as leaf Mg concentration increased (Fig. 2c–d). Generally, higher plant DWs were obtained at 12–22 mM nutrient solution K concentrations (Table 4).

Table 4. Yield (fresh weigh, 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					
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 part fruits in the photograph referred to marketable fruits and non-marketable fruits, respectively. Values are the means of three replicate pots. Means in each line followed by same letters are not significantly different at $P<0.05$ according to Fisher's LSD test.

The total yield of cherry tomato was highest when solution K concentration 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; Fig. S2).

Discussion

Mg application affected photosynthate 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) [26]. Increased yield and dry matter accumulation in response to proper Mg application was 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 the later studies, Hao and Papadopoulos (2004) explained it by decrease of biomass and fruit biomass allocation in the low Mg treatment [15]. We also observed that lower plant DW and HI reduced yield in response to low Mg application (< 1 mM).

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 [27] and spinach

[28] plants, and Andersson (2008) demonstrated that the involvement of rubisco in CO_2 fixation was adversely affected by poor Mg supply [29].

The decrease of 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 have been 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 [13]. Farhat et al. (2016) attributed it to preference of Mg transported to source leaves to prevent severe declines in photosynthetic activity [19]. Mg starvation seems to have a direct detrimental effect on function and/or structure of phloem loading [19, 27, 30, 31].

Relationships between 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 [11]. 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 was about 4.67 and 5.52 g kg^{-1} in these periods. SPAD reading is an indicator of leaf chlorophyll concentration, which determines photosynthetic rate to a great extent [19]. So photosynthesis rates also fitted this model, and the critical leaf Mg concentration for photosynthesis rates was about 4.41 and 5.01 g kg^{-1} at the first and second harvests. A previous report indicated that maintenance of normal plant growth requires 4.0-6.0 g kg^{-1} leaf Mg concentration in tomato plants at anthesis, and the marginal concentration in first harvest period was 3.0 g kg^{-1} [32]. The linear-with-plateau model was applied to dry matter formation too, and the critical leaf Mg concentration was about 4.38 and 4.50 g kg^{-1}, slightly lower than those for the photosynthesis rate. Similarly, dry matter accumulation in *Pinus radiata* was shown to be inhibited by Mg deficiency [33]. Hauer-Jákli and Tränkner (2019) confirmed 3.9 g kg^{-1} as the critical leaf Mg concentration for tomato dry matter accumulation [34] based on the results of Kasinath et al. (2014), which was lower than this study [35]. The different critical leaf Mg concentrations among SPAD reading, photosynthesis rate and plant dry matter accumulation indicated that sufficient Mg supply can guarantee the chlorophyll concentration and the production of photosynthates, which was consistent with the result that plant growth reduction appears as a later response compared with chlorophyll content decrease to Mg deficiency [14]. Clear relationships were observed between SPAD reading, photosynthesis rate, plant dry matter accumulation and leaf Mg concentration. It may be explained by the adequate Mg supply during initial growth stages [34]. These results clearly demonstrate the importance of Mg supply in maintaining strong photosynthesis to produce cherry tomato dry matter.

Two-side effects of Mg application on the plant K and Ca content

In the second harvest period, the plant K and Ca content of cherry tomato was first increased with Mg concentration in solution before 1 mM and then decreased. It was indicated by the plant dry matter

accumulation and the leaf K and Ca concentration.

The plant dry matter accumulation increased first with solution Mg concentration increased but decreased when 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 [33, 34, 36], the inhibitive effects observed in this study have rarely been reported due to the difficulty of detecting toxicity symptoms, even at high concentrations [37]. 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 [38]. Moreover, Shaul (2002) and Koch et al. (2019) associated this decrease with K^+ transport inhibition from the cytosol to the stroma, disequilibration within the chloroplast and interference in transport events across the tonoplast [9, 18].

Low leaf K and Ca levels among high Mg supply treatments indicate antagonistic effects among these cations [24]. 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 [32, 39]. Leaf Ca concentration also decreased in higher Mg supply treatments, but was higher than 10 g kg^{-1} [32]. 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 seven-fold higher K distribution than Ca distribution in pea seeds [24], and Karley and White (2009) also noticed this phenomenon [40].

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 [26], sugarbeet [41], green bean [42], potato [43], rice [44], grape [45] and apple [46]. The present study showed that an increasing K concentration in solution adversely affected the leaf Ca and Mg concentrations. Leaf Mg and Ca were lower than 4.7 and 10.0 mg kg^{-1} when solution K concentrations exceeding 17 mM under the 2 mM solution Mg supply, indicating Mg (from the former experiment in this study) and Ca deficiency [32]. 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} [32, 39]. These findings may explain the influence of K supply levels on total yields and plant DWs. Which was in line with Yurtseven et al. (2005), who reported that significant yield increases with increasing K application [47]. However, Nzanza (2006) found that none of the applied K treatments had any significant effect on marketable tomato yield [26]. The difference could be explained by the maximum K supply concentration, 9 mM in the study by Nzanza (2006) and 27 mM in this study [26].

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 [48]. 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 [44]. Toumi et al. (2016) also reported that Mg uptake was inhibited by increase of K/Mg in the nutrient solution in *Vitis vinifera*, but no significant differences in leaf Ca concentration were detected among treatments [45].

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 is 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 can satisfy the requirements for optimized SPAD, photosynthesis rate and plant dry matter accumulation combined with high fruit yield. Those leaf Mg concentrations are slightly higher than that reported in a previous study, which demonstrated that tomato dry matter accumulation responded best at 3.9 g kg^{-1} plant Mg concentration [34-35]. 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 also showed by Guo et al. (2015) when Mg concentration in soil solution was higher than 8.5 mM [17].

Mg deficiency is a common problem in growth media fertilized only with N, P and K [7, 19]. 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 [49-50]. Therefore, K concentrations in soilless culture system should be managed to supply sufficient leaf K to achieve high yield, while avoiding Mg uptake suppression due to excessive K. Consta´n-Aguilar et al. (2014) observed that cherry tomato fruit dry matter was higher when K concentrations ranged from 10 to 15 mM [51]. The current study indicates that 12 mM K in solution is optimal, based on our nutrient uptake and photosynthate production results. We also established relationships among leaf K or Mg concentration with cherry tomato dry matter in this study, which may be useful for understanding the mechanisms of yield formation in soilless vegetable production systems.

Conclusions

Inadequate Mg supply impairs yield by influencing production and distribution of photosynthesis products. When Mg supply in solution was 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, and also implying that sufficient Mg supply can guarantee the 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 nutrition. An interruptive effect of K supply on leaf Mg and Ca concentrations was also found in this study. Generally, 1–4 mM Mg in solution was needed to satisfy the requirements for optimized SPAD, photosynthesis rate and plant dry matter accumulation combined with high fruit yield. Similarly, 12 mM of K concentration in solution was recommended based on nutrient uptake and photosynthate production in the substrate cherry tomato cultivation system.

Methods

Two experiments were conducted under greenhouse conditions from March to August 2016 and March to July 2017. Cherry tomato (L. esculentum Mill. cv. Qianxi) seeds were procured from Shandong Nongyou Seeds Co., Ltd., China. Seeds were sown in 50-cell plug trays filled with a commercial substrate and were germinated and grown in a temperature-controlled chamber. After four true leaves had become fully unfolded (about 30 days), seedlings were transplanted into coconut chaff and fertilized with nutrient solution.

In the Mg experiment, cherry tomato plants were planted in coconut chaff at seven Mg levels (0, 0.5, 1, 2, 4, 8 and 16 mM) together with 12 mM K supplied in nutrient solution. In the K experiment, we applied five levels of K (7, 12, 17, 22, and 27 mM) and 2 mM Mg in nutrient solution. Two side rows were planted as guard rows in each treatment; thus, we planted a total of nine and seven plant rows for the Mg and K experiments, respectively, and there were fifteen plants in each row. The treatments were replicated three times and each treatment had an independent fertigation system. In all treatments, we supplied 240 $mg{\cdot}L^{-1}$ N and 35 $mg{\cdot}L^{-1}$ P during the seedling and anthesis periods in all treatments, while 230 mg L^{-1} N and 22 mg L^{-1} P 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 adjusted pH to 5.5-7.0 using nitric acid (HNO_3) or sodium hydroxide (NaOH) every two days.

At the 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 were digested with HNO_3-H_2O_2 (6 mL HNO_3 and 2 mL H_2O_2) 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, USA). Standard materials for K, Ca and Mg analyses (IPE126) were obtained from Wageningen Evaluation Programs for Analytical Laboratories (WEPAL, Netherlands). In the Mg experiment, we

randomly selected one middle leaf from the fourth branch on plant in each repetition in the morning (09:00–12:00) under natural light to measure photosynthetic rate using an LC-ProSD system (eADC BioScientific Ltd., UK); The SPAD readings were taken with a chlorophyll meter (SPAD-502, Minolta, Japan) and recorded as a mean of 6 measurements for each individual middle leaf from the third or fourth branch on plant. This procedure was followed at anthesis and repeated during the first and second harvests.

SAS v. 8.0 (SAS, Cary, NC, USA) and SPSS v. 20.0 (SPSS, Chicago, IL, USA) software were used for statistical analyses. Means were compared using analysis of variance (ANOVA), followed by Fisher's least significant difference [LSD] test at a significance level of $P < 0.05$.

Abbreviations

Mg: Magnesium; K: potassium; Ca: calcium; HI: harvest index; DW: dry weight.

Declarations

Ethics approval and consent to participate

The Cherry tomato seed (Qianxi) is a common and broadly cultivated variety in China. The seed was bought from Shandong Nongyou Seeds Co., Ltd., China. There is no transgenic technology or material in this study, therefore the ethics approval is not required. The experimental research on plants performed in this research complied with institutional, national and international guidelines. The study was conducted in accordance with local legislation and granted by China Agricultural University.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

XC, CZ and DL planned and designed the research; XG, BL, CW and CL performed the experiments and did the sample test; XG and XW collected and analysed the data and wrote this paper; XC, CZ and DL helped in data analysis and manuscript. All authors have read and approved the final manuscript.

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Additional Files

Additional file 1: **Figure S1** Mean daily temperatures in the vegetation period during the Mg and K experiments in the greenhouse. The data of temperatures recorded every two hours.

Additional file 2: **Figure S2** Effects of K concentrations in solution on plant potassium (K), calcium (Ca), and magnesium (Mg) uptake by cherry tomato plants. Values are means ± standard error (SE) among three replicates. For each nutrient, means with the same letters did not differ significantly at $P < 0.05$ (Fisher’s least significant difference [LSD] test).

Figures

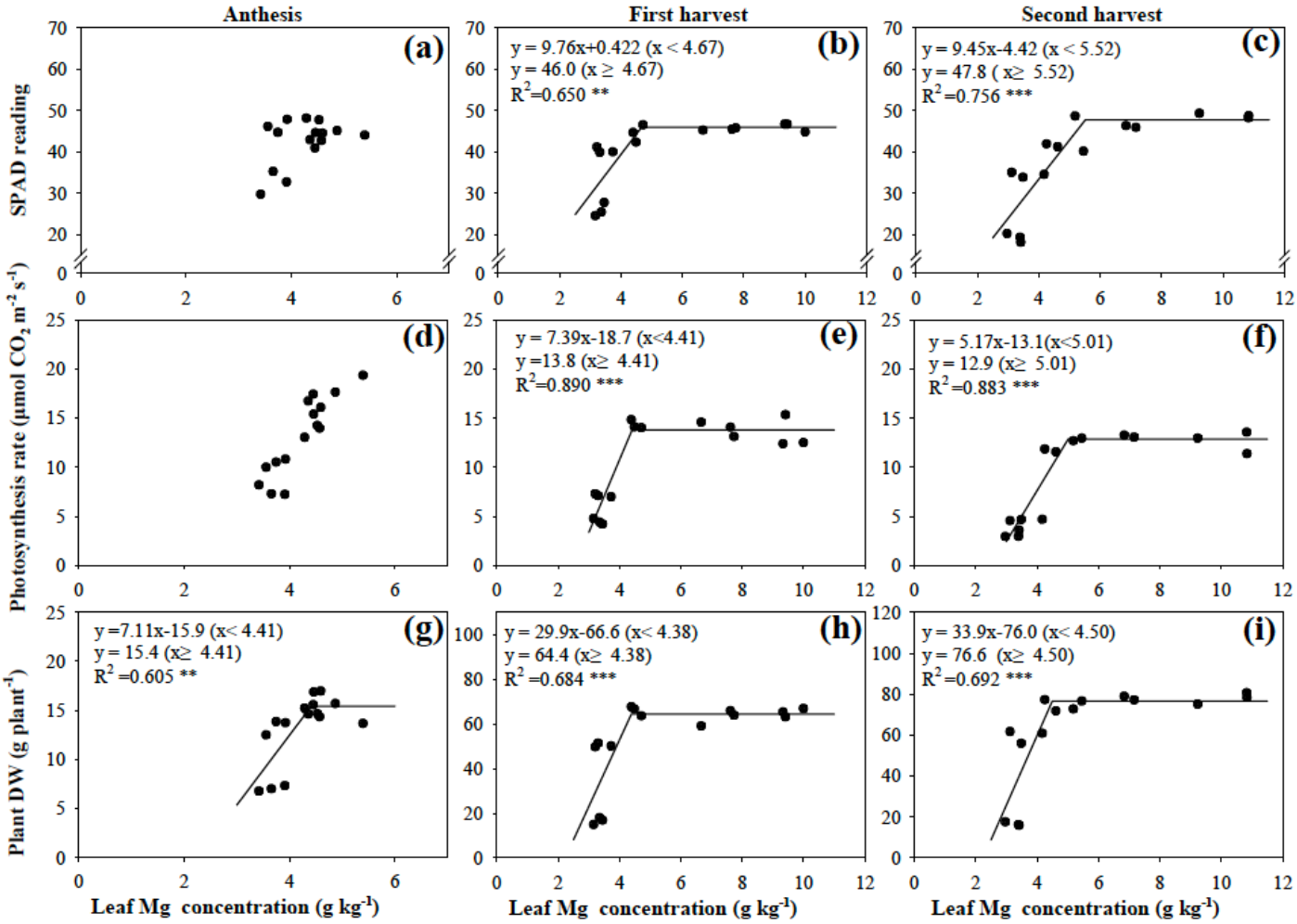

Figure 1

SPAD reading, photosynthesis rate and plant dry weight (DW) of cherry tomato plotted against leaf Mg concentration. The correlation were studied at anthesis (a, d, g), first harvest (b, e, h) and second harvest period (c, f, i) at Mg nutrient solution concentrations of 0-4 mM (n = 15).

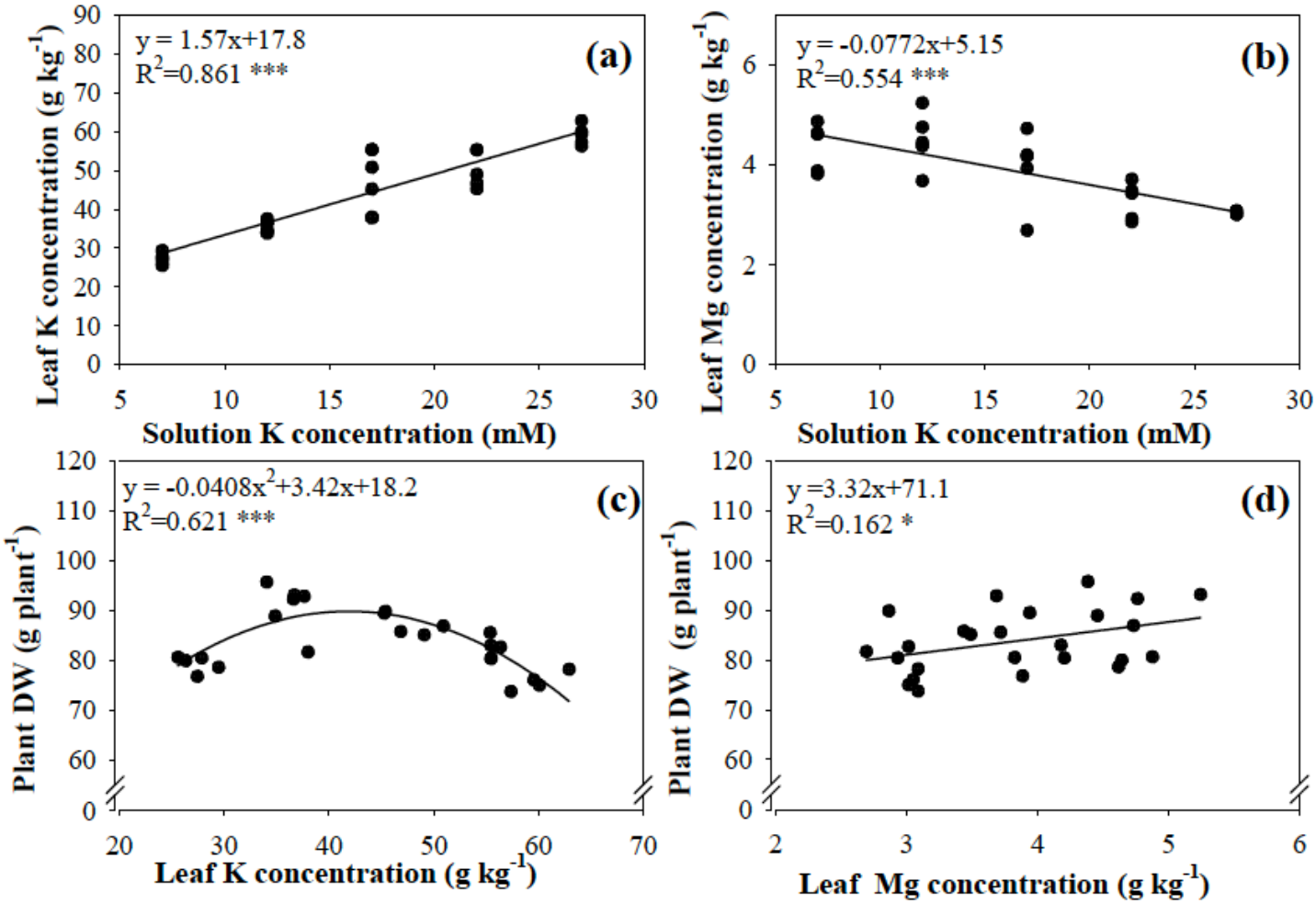

Figure 2

Effected of solution K concentration on leaf K, Mg concentrations and the plant dry weight (DW). The relationships between solution K concentration and leaf K (a) and leaf Mg (b) concentrations, and between leaf K (c) and leaf Mg (d) concentrations and plant dry weight (DW) were studied in the second fruit harvest period.

Supplementary Files

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