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Potassium–calcium antagonistic interaction under tomato magnesium deficiency and magnesium fertiliser regulation in solar greenhouse

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RESEARCH ARTICLE

Abstract

This study sought to clarify the antagonistic interactions of potassium (K) and calcium (Ca) to magnesium (Mg) under a deficiency of Mg in tomato. Tomato leaves and soil samples that had differing levels of Mg deficiency were collected to study the relationship between symptoms of Mg deficiency and contents of soil K and Ca. Four different Mg fertiliser treatments were conducted to analyse the regulation of Mg for soil K, Ca and Mg. The results showed the following: (1) The yield of tomatoes decreased significantly with an increase in Mg deficiency, and the yield of tomatoes with moderate (MD) and severe (SD) Mg deficiency decreased by 38.02% and 59.53%, respectively, compared with treatments without Mg deficiency (ND). (2) The cation saturation ratio of K^+ ($CSRK^+$) was significantly higher with MD and SD compared with ND, while the $CSRMg^{2+}$ was lower. The soil K/Mg and Ca/Mg values were higher than the critical value of imbalance. (3) The soil exchangeable K, $CSRK^+$, Ca/Mg and K/Mg under SD increased significantly when compared with that under ND. (4) The content of Mg in tomato leaves and its yield were significantly negatively correlated with soil exchangeable K, $CSRK^+$ and K/Mg. (5) With the increase in application of Mg fertiliser, the soil exchangeable K content, K/Mg and $CSRK^+$ decreased significantly, while the Ca/K increased. The soil exchangeable K content, K/Mg and $CSRK^+$ with 90 kg/ha $MgSO_4$ and 234 kg/ha K_2O applied (M2K1 treatment) were the lowest among all treatments. (6) The yields of tomatoes and uptake of Ca and Mg increased as supply of Mg increased. (7). Reducing the application of K was a much more efficient way to decrease soil K/Mg and restore cation imbalance than providing Mg fertiliser in calcareous soil.

Keywords: calcareous soil, cation ratio, soil nutrient, yield

1. Introduction

Magnesium (Mg) is one of the essential nutrients for plant growth that accounts for approximately 0.05 to 0.7% of their dry weight. It is an important component of chloroplasts. With a sufficient supply of Mg, approximately 20% of the total Mg is combined with chlorophyll (Marschner, 2012). As a central atom of the chlorophyll molecule (Huber and Maury, 1980), Mg plays an important role in photosynthesis, carbohydrate formation and protein synthesis (Guo *et al.*, 2016). The application of Mg fertiliser helps to increase chlorophyll content of plants. Chapagain and Wiesman (2004) stated that the chlorophyll content of tomato leaves with application of potassium chlorate and magnesium chloride was significantly higher than that with potassium chlorate, suggesting that chlorophyll molecules can absorb quantum light only when combined with Mg ions (Mg^{2+}). Essentially, a few molecules of Mg^{2+} (at a concentration of 5 mmol/L) induce the thylakoid membrane to form granules that are

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more conducive to capturing light energy and transferring energy (Kaftan *et al.*, 2002). In addition, Mg^{2+} may act on reaction centres and antenna pigments as well as some electron carriers on the membrane at the molecular level (Genty *et al.*, 1989; Gupta and Berkowitz, 1989). Similar studies have shown that under the radiation of light, Mg^{2+} on the chloroplast thylakoid membrane can be exchanged with hydrogen ions in the matrix, leading to an increase in the concentration of Mg^{2+} and pH value in the matrix, an activation of ribulose bisphosphate carboxylase, and an increasing Michaelis–Menten constant (K_m) and maximum velocity of enzymatic reaction (V_{max}) (Cacco *et al.*, 2010; Keitaro *et al.*, 2014). It is more conducive to the fixation and assimilation of carbon dioxide (Tatagiba *et al.*, 2016).

Mg deficiency may cause the disintegration of plant chloroplasts, a reduction in the photosynthetic rate, limitation of transport of assimilation products and a decrease in crop yield and quality (Verbruggen and Hermans, 2013). When Mg becomes deficient, plant transpiration and photosynthesis are immediately inhibited (Hermans and Verbruggen, 2005; Hermans *et al*, 2004; Kobayashi *et al.*, 2013). Crop yield and biomass are usually substantially reduced when the level of Mg is low. Moreover, deficiency in Mg is significantly correlated with the nutrient uptake of plants (Huang *et al.*, 2019; Jin *et al.*, 2016).

A deficiency of Mg corresponds to a direct lack of Mg (Aitken *et al.*, 1999), but the antagonistic interaction can also be caused by an imbalanced input of fertiliser (Hermans *et al.*, 2004). Potassium (K^+) and calcium ions (Ca^{2+}) are related to the absorption of Mg^{2+} (Chapagain and Wiesman, 2004; Gransee and Führs, 2013). When a large amount of potassium (K) is supplied, it decreases the content of Mg in plant, particularly in plant roots (Ding *et al*, 2006; Omar and Kobbia, 1966). In the past, experimental antagonistic interactions between K^+ and Mg^{2+} occurred during the transport from roots to shoots (Ohno and Grunes, 1985). A high availability of Ca^{2+} is sensitive to Mg uptake (Marschner, 2012). Although there is some information on the interaction between K, Ca and Mg in forests, grasses and arable crops, there is currently no information regarding vegetables such as tomato (Guo *et al.*, 2016).

The application of fertiliser is an effective way to relieve the deficiency of Mg. Similar results have shown that the application of gray Mg limestone on acidic soils in Malaysia can effectively increase the content of Mg in soil and rice yield, and in addition reduced the toxicity of iron and aluminum (Panhwar *et al.*, 2014). However, fewer studies have been conducted in calcareous soils enriched in Mg.

In this study, tomato leaves and soil with different levels of Mg deficiency were collected to clarify the K–Ca–Mg antagonistic interaction in calcareous soil in a greenhouse. In addition, a test of Mg fertiliser was conducted to evaluate the effect of Mg fertiliser on the balance of K, Ca and Mg in soil.

2. Methods and materials

Study site

The effect of Mg deficiency on K and Ca antagonism mechanism

The study was conducted at solar greenhouses of Dazhai Town in Yangling Agricultural High-Tech Industry Demonstration Zone, Shaanxi Province, China (latitude 34° 16' N, longitude 108° 4' E). The greenhouses were built in 2009 and characterised by calcareous soil. Tomato plants were grown each autumn and winter, and each cropping cycle was separated by plantings of tomato, cucumber or watermelon during the spring.

The experiment was conducted on 5 August, the sowing date of tomato. Samples were collected on 15 November when the Mg deficiency became apparent on tomato leaves during fruit period. According to different symptoms shown in leaves in different greenhouses, the level of Mg deficiency were divided into three parts as follows: (1) no Mg deficiency (ND): no symptoms of Mg deficiency in leaves were observed; (2) moderate Mg deficiency (MD): only half of the leaves showed symptoms of Mg deficiency; the upper leaves showed no symptoms and chlorosis; (3) severe Mg deficiency (SD): the upper and lower part of leaves showed symptoms of Mg deficiency, and some leaves had died. Based on the classification of Mg deficiency, three greenhouses were selected with which different symptoms in leaves were observed. Each treatment was repeated for three times. The total amount of fertiliser and irrigation are shown in Table 1.

The effect of Mg fertiliser on soil K, Ca and Mg

The study on the effect of Mg fertiliser was conducted from September to March of the next year in the solar greenhouse No. 11 of Wuquan Town, Shaanxi Province. China (latitude 34° 16' N, longitude 108° 4' E), where severe symptoms of Mg deficiency appeared. The ground was covered with a polyethylene film (PE), and the front crop was tomato with a severe deficiency of Mg.

The experiment was conducted using two types of fertilisers: Mg and K. There were three levels of Mg fertiliser as follows: (1) M0 at a rate of 0 kg/ha; (2) M1 at a rate of 45 kg/ha and (3) M2 at a rate of 90 kg/ha. There were two levels of K fertiliser as follows: (1) K1 at a rate of 234 kg/ha, and (2) K2 at a rate of 414 kg/ha. M1 and K2 were established on the basis of local farming practices. K1 was established on the basis of local recommended amount.

Table 1. Fertilisers and irrigation with different levels of tomato Mg deficiency in solar greenhouse.

Levels of Mg deficiency	Organic fertiliser (t/ha)	Chemical fertiliser (kg/ha^2)			Total irrigation (m^3/ha)
		N	P_2O_5	K_2O	
ND (*n* = 3) No deficiency	19 ± 6^b	240 ± 68^b	287 ± 126^a	310 ± 118^b	1,447 ± 351^a
MD (*n* = 3) Moderate deficiency	14 ± 4^b	281 ± 69^b	239 ± 70^a	305 ± 70^b	1,401 ± 186^a
SD (*n* = 3) Severe deficiency	34 ± 7^a	410 ± 21^a	396 ± 82^a	546 ± 50^a	1,350 ± 464^a

n is the number of greenhouse soil samples.
Different letters indicated that the difference was significant at $P < 0.05$.

Table 2. Soil properties before planting in greenhouse.

Soil layer (cm)	Nitrate nitrogen (mg/kg)	Available phosphorus (mg/kg)	Available potassium (mg/kg)	Exchangeable potassium (mg/kg)	Exchangeable calcium (mg/kg)	Exchangeable magnesium (mg/kg)
0–20	83.90	98.30	259.50	318.00	3993.75	289.94
20–40	46.87	68.13	126.11	134.00	4100.00	211.94

Table 3. Treatments of experiment and fertiliser rate.

Treatment		N (kg/ha)	P_2O_5 (kg/ha)	K_2O (kg/ha)	$MgSO_4$ (kg/ha)
Base fertiliser		135	405	135	0
Top dressing	Mg0K2	216	57	279	0
	Mg1K2	216	57	279	45
	Mg2K2	216	57	279	90
	Mg2K1	216	57	99	90

Mg0K2: 0 kg/ha $MgSO_4$, 414 kg/ha K_2O; Mg1K2: 45 kg/ha $MgSO_4$, 414 kg/ha K_2O; Mg2K2: 90 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K1: 90 kg/ha $MgSO_4$, 234 kg/ha K_2O.

Four treatments – Mg0K2, Mg1K2, Mg2K2 and Mg2K1 – were arranged in a completely randomised design with three repetitions. The size of plot was 15.08 m^2. The tomato plants were grown on 9 September. The soil properties before planting are shown in Table 2. Before planting, 135 kg/ha N, 405 kg/ha P_2O_5 and 135 kg/ha K_2O were applied. Top dressing was applied on 6 November, 18 November and 2 December with the same amount. The total amount of fertilisers applied is shown in Table 3. The plants were harvested on 15 March of the next year.

Sampling and analysis

Soil and leaf samples were collected to study the changes in K, Ca and Mg under different symptoms of Mg deficiency. Soil samples for each greenhouse were collected from a depth of 0 to 0.2 m, and tomato leaves from both the bottoms and tops were cleaned and oven-dried at 60 °C on 15 November.

To analyse the effect of Mg fertiliser on soil chemical properties, the soil samples were selected from a depth of 0 to 0.2 m and the tomato samples were selected and divided into root, stem, upper leaf, lower leaf and fruit after the tomatoes were harvested on 15 March.

The exchangeable K, Ca and Mg contents of soil samples were extracted using a modified version of the sodium acetate (CH_3COONa) method at pH 8.2 (Bao, 2005). The exchangeable K was determined using a flame photometric detector (FPD) (Taomsun-6400A, Shanghai, China), and the exchangeable Ca and Mg were measured by atomic absorption spectrophotometry.

The contents of K, Ca and Mg in both upper and lower leaves of tomato were extracted using the dry-ash method. The amount of K was measured using FPD, and the amounts of Ca and Mg were measured by atomic absorption spectrophotometry.

Statistical analysis

Since the exchangeable cations of calcareous soil are primarily K^+, Ca^{2+}, and Mg^{2+}, the cation saturation ratios (CSR) of K^+, Ca^{2+}, Mg^{2+} were expressed as follows:

$$\mathrm{CSRK^+} = m(\mathrm{K^+}) / m(\mathrm{K^+} + \mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})$$

$$\mathrm{CSRCa^{2+}} = m(\mathrm{Ca^{2+}}) / m(\mathrm{K^+} + \mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})$$

$$\mathrm{CSRMg^{2+}} = m(\mathrm{Mg^{2+}}) / m(\mathrm{K^+} + \mathrm{Ca^{2+}} + \mathrm{Mg^{2+}})$$

The data were analysed using a one-way ANOVA variance by SAS 8.1. The Tukey test was used to compare means when there was a significant factor effect on the analysis of variance. The significance levels were fixed at $P < 0.05$. Graphs were drawn using MS Excel.

3. Results

The effect of a deficiency of Mg on mechanism of K and Ca antagonism

A deficiency of Mg affected not only the contents of K, Ca and Mg in leaves but also the yield of tomatoes. The concentrations of K, Ca and Mg in both upper and lower leaves were significantly reduced with MD and SD in comparison to ND, but there was no difference between MD and SD (Table 4). The yield of tomatoes decreased significantly when Mg deficiency became more serious. Compared with ND, the yield of tomatoes under MD and SD was decreased by 38.02% and 59.53%, respectively (Figure 1).

Figure 2 shows that the soil exchangeable K content and $CSRK^+$ approximately correlated with enhanced Mg deficiency. The soil exchangeable K content under SD was significantly higher than that with ND (+69.94%) and MD (+35.78%), respectively. The soil $CSRK^+$ under MD and SD increased by 21.74% and 55.73%, respectively, when compared with those under ND. In contrast, the soil exchangeable Mg content and $CSRMg^{2+}$ were significantly lower under SD compared with those of ND and MD. However, there was no significant difference among the soil exchangeable Ca content and $CSRCa^{2+}$ under different levels of Mg deficiency.

With the enhancement of Mg deficiency, the soil K/Mg (coml/cmol) and Ca/Mg (coml/cmol) increased (Figure 3), while the soil Ca/K (coml/cmol) decreased. The K/Mg of soil under ND, MD and SD were 0.72, 0.88 and 1.35, respectively. The Ca/Mg of soil with SD was significantly higher than that of others. The Ca/K values of soil under ND, MD and SD were 10.65, 8.61 and 6.76, respectively. The Ca/K of soil under MD and SD were 19.15% and 36.53%, respectively, significantly lower than that under ND.

The correlation between yield, K, Ca and Mg of tomato and soil properties is shown in Table 5. The content of K and concentration of Mg in both upper and lower leaves were negatively correlated with soil exchangeable K, $CSRK^+$ and K/Mg and positively correlated with $CSRCa^{2+}$and Ca/K. The content of Ca in lower leaves was negatively correlated with soil exchangeable K, $CSRK^+$ and K/Mg but positively correlated with $CSRCa^{2+}$ and Ca/K. The content of K in both upper and lower tomato leaves was correlated with Ca/K in 99% cases, and the content of K in lower leaves was correlated with $CSRK^+$ in 99% cases. The concentration of Mg in tomato leaves

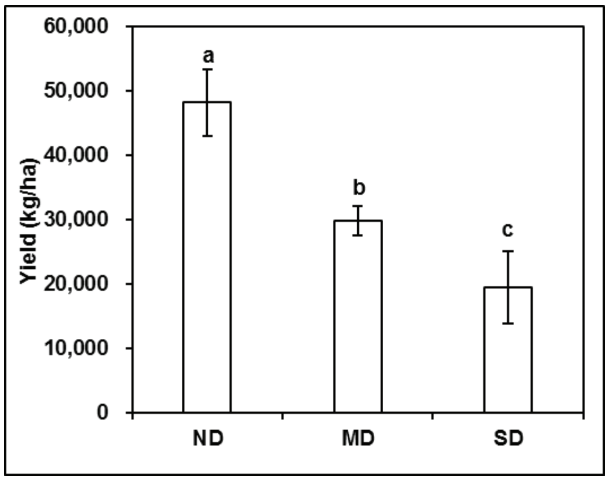

Figure 1. The tomato yields affected by different levels of Mg deficiency.

ND, no Mg deficiency; MD, moderate Mg deficiency; SD, Severe Mg deficiency. Different letters indicated the difference was significant at $P < 0.05$.

Table 4. The nutrient content in (a) upper and (b) lower tomato leaves displayed at different levels of Mg deficiency.

Mg deficiency level		Leaf weight (g/leaf)	K		Ca		Mg	
			Concentration (g/kg)	Accumulation (mg/leaf)	Concentration (g/kg)	Accumulation (mg/leaf)	Concentration (g/kg)	Accumulation (mg/leaf)
Upper leaves	ND	2.98[a]	44.97[a]	134.90[a]	65.49[a]	196.47[a]	7.18[a]	21.75[a]
	MD	4.05[a]	32.13[b]	128.79[a]	42.82[b]	172.95[a]	4.81[b]	19.57[a]
	SD	3.79[a]	27.22[b]	102.44[a]	49.55[b]	185.67[a]	4.04[b]	15.35[a]
Lower leaves	ND	5.52[a]	30.73[a]	172.20[a]	91.17[a]	502.94[a]	10.07[a]	55.87[a]
	MD	5.27[a]	24.82[b]	127.68[a]	70.41[b]	372.23[a]	7.93[b]	42.08[a]
	SD	5.88[a]	21.55[b]	126.53[a]	64.48[b]	381.55[a]	6.95[b]	41.18[a]

ND, no Mg deficiency; MD, moderate Mg deficiency; SD, severe Mg deficiency.
Different letters indicated that the difference was significant at $P < 0.05$.

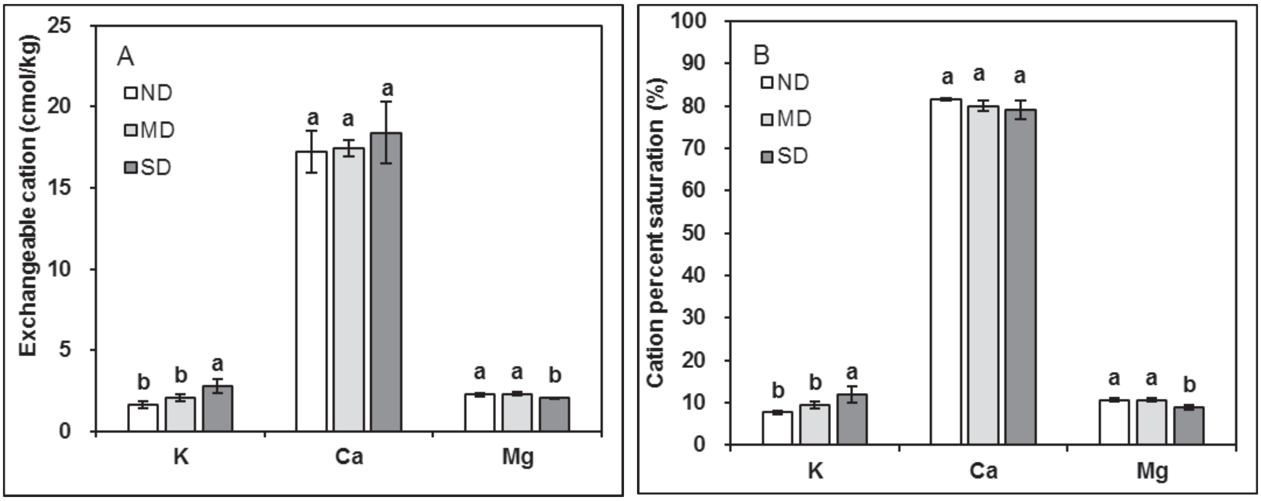

Figure 2. (a) Exchangeable content and (b) cation saturation ratios of soil K, Ca and Mg under different levels of Mg deficiency.
ND: no Mg deficiency; MD moderate Mg deficiency; SD: Severe Mg deficiency. Different letters indicated that the difference was significant at $P < 0.05$.

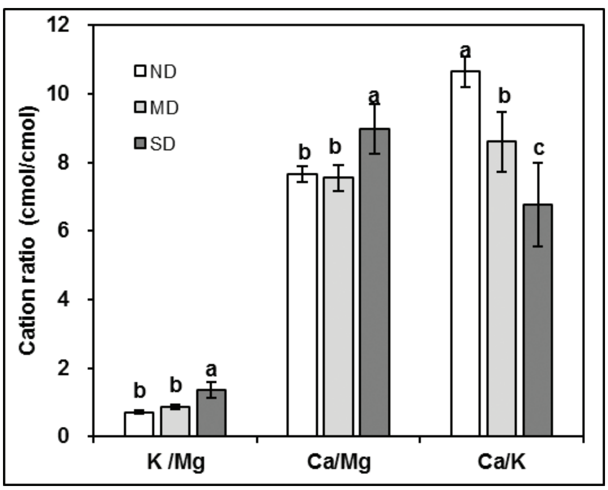

Figure 3. The ratios of soil K/Mg, Ca/Mg and Ca/K under different levels of Mg deficiency.
ND, no Mg deficiency; MD, moderate Mg deficiency; SD, Severe Mg deficiency. Different letters indicated that the difference was significant at $P < 0.05$.

was correlated with $CSRK^+$ and Ca^{2+}/K^+ in 99% cases. The tomato yield was negatively correlated with K, $CSRK^+$ and K/Mg in 95% and positively correlated with Ca/K in 99% cases.

The effect of mg fertiliser on soil chemical properties

The application of Mg fertiliser caused a decrease in soil content of exchangeable K (Figure 4). Compared with the Mg0K2 treatment, the content of soil exchangeable K under Mg1K2 and Mg2K2 treatments decreased significantly by 15.78% and 27.74%, respectively. There was no significant difference in the soil exchangeable Ca content under different fertiliser treatments. With the raise of application of Mg fertiliser, the content of soil exchangeable Mg increased insignificantly. In comparison with the Mg0K2, Mg1K2 and Mg2K2 treatments, the exchangeable K content under Mg2K1 treatment decreased significantly by 15.78, 14.20 and 4.72%, respectively. There were no differences in exchangeable Ca content under different fertiliser treatments.

As the Mg fertiliser increased, the soil $CSRK^+$ decreased, while the soil $CSRMg^{2+}$ and $CSRCa^{2+}$ increased. The soil $CSRK^+$ under Mg1K2, Mg2K2 and Mg2K1 treatments was 13.39, 27.21 and 29.12% lower than that under Mg0K2 treatment, respectively, and the difference between Mg2K2 and Mg2K1 treatments and Mg0K2 treatment was significant. The soil $CSRCa^{2+}$ of Mg1K2, Mg2K2 and Mg2K1 treatments increased but were not significant (Figure 4).

Compared with Mg0K2, the soil Ca/Mg under Mg2K1 treatment decreased by 16.89% (Figure 5). However, there were no significant differences among the four treatments. Mg fertiliser had no significant effect on soil Ca/Mg. Reducing the application of K fertiliser at the same time with the application of Mg fertiliser can greatly reduce soil Ca/Mg. The soil K/Mg decreased with an increase in application of Mg fertiliser. The soil K/Mg in Mg2K2 treatments was 26.61% lower than that in Mg0K2, while no differences were observed between the soil K/Mg in M1K2 and Mg0K2. The soil K/Mg in Mg2K1 treatment was the lowest among four treatments and was 41.94% and 20.88% lower than that of Mg0K2 and

Table 5. Correlation between yield, K, Ca, Mg of tomato and soil exchangeable ions and cation saturation ratios.

Soil properties	Upper leaves			Lower leaves			Yield (kg/ha)
	K (g/kg)	Ca (g/kg)	Mg (g/kg)	K (g/kg)	Ca (g/kg)	Mg (g/kg)	
Exchangeable K^+ (mg/kg)	−0.74*	−0.37	−0.83**	−0.84**	−0.72*	−0.78*	−0.73*
Exchangeable Ca^{2+} (mg/kg)	−0.08	−0.07	−0.34	−0.30	0.10	−0.12	−0.15
Exchangeable Mg^{2+} (mg/kg)	0.50	−0.02	0.40	0.27	0.47	0.44	0.60
$CSRK^+$ (%)	−0.78*	−0.40	−0.82**	−0.84**	−0.80**	−0.82**	−0.76*
$CSRCa^{2+}$ (%)	0.72*	0.44	0.69*	0.78*	0.82**	0.77*	0.63
$CSRMg^{2+}$ (%)	0.53	0.15	0.66	0.56	0.40	0.53	0.63
Ca/Mg (cmol/cmol)	−0.40	−0.06	−0.53	−0.42	−0.25	−0.39	−0.51
Ca/K (cmol/cmol)	0.86**	0.56	0.89**	0.93**	0.83**	0.85**	0.83**
K/Mg (cmol/cmol)	−0.73*	−0.30	−0.80**	−0.78*	−0.72*	−0.78*	−0.75*

*Correlation was significant in 95% cases; **correlation was significant in 99% cases.

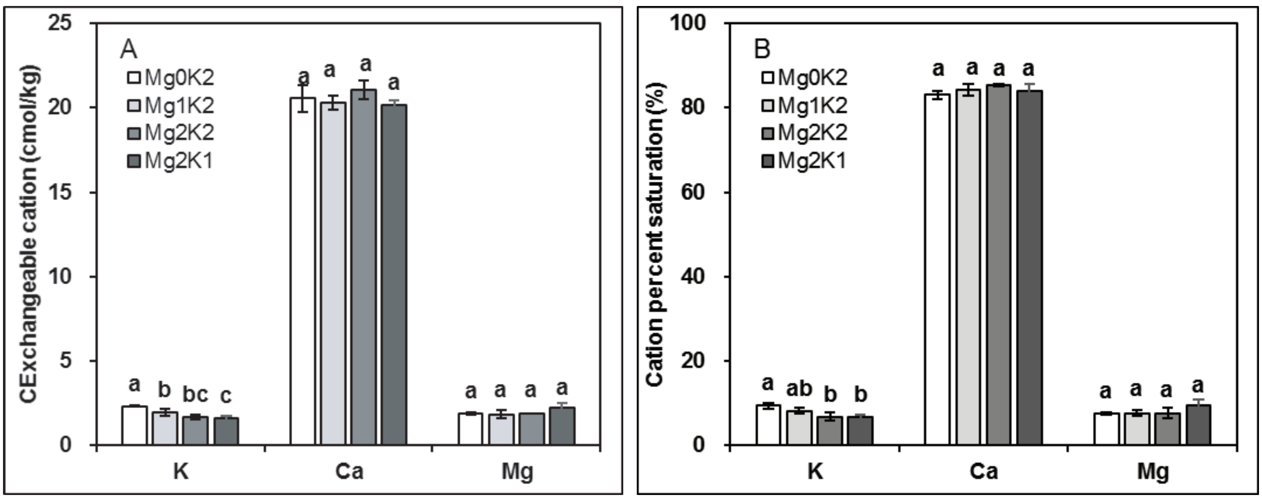

Figure 4. (a) Exchangeable content and (b) cation saturation ratios of soil K, Ca and Mg under different Mg fertiliser treatments. Different letters indicated that the difference was significant at $P < 0.05$.

Mg2K2, respectively. With increase in the Mg fertiliser, the soil Ca/K increased. The soil Ca/K in Mg1K2, Mg2K2 and Mg2K1 increased by 17.25, 42.39 and 42.84%, respectively, when compared with those in Mg0K2 treatment.

The effect of fertiliser on tomato yield and Mg, K and Ca contents

A deficiency of Mg was observed in every treatment. As shown in Table 6, the dry matter of tomato stems and fruits increased, and the dry matter of tomato leaves decreased with the increase in Mg fertiliser. The dry matter of tomato fruit increased by 1.19, 3.19 and 2.55% in M1K2, M2K2 and M2K1 treatments, respectively, compared with that of M0K2. However, the differences were not significant among treatments.

When M2K1 was compared with M2K2 (Table 7), the Mg content of tomato fruit decreased by 31.45%, and the K supply decreased by 43.48%. The K content of tomato stem increased as supply of Mg increased, while the K content of lower leaves of tomato decreased. When M2K1 was compared with M2K2, the K content of tomato stems, leaves and fruits decreased significantly with decrease in supply of K. The Ca content of tomato roots and upper leaves decreased, while those of tomato stems and fruit increased as supply of Mg increased. The Ca content of tomato fruit increased by 9.78, 54.46 and 35.11% under M1K2, M2K2 and M2K1 treatments, respectively. There was no difference in the Mg content of tomato roots, stems and leaves among the four treatments. The Mg content of tomato increased as amount of Mg fertiliser increased. The Mg content increased by 30.83, 94.37

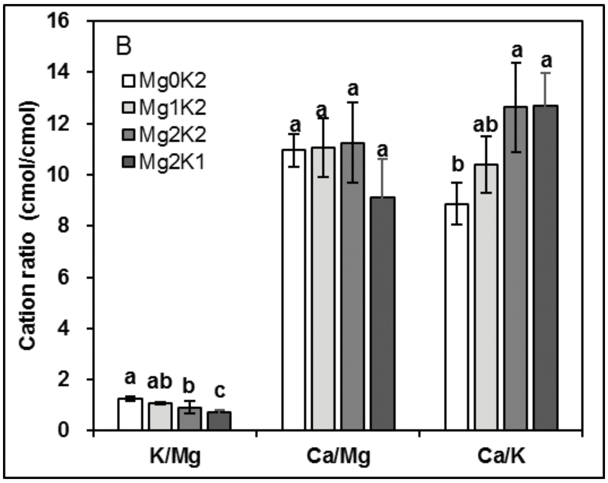

Figure 5. The ratio of soil K/Mg, Ca/Mg and Ca/K under different fertiliser treatments.
ND, no Mg deficiency; MD, moderate Mg deficiency; SD, severe Mg deficiency. Different letters indicated that the difference was significant at $P < 0.05$.

Table 6. Effect of different fertiliser rates on tomato dry matter (kg/ha).

Treatments	Roots	Stems	Leaves	Fruits
M0K2	241.43[a]	799.38[a]	1087.45[a]	3213.42[a]
M1K2	188.49[a]	837.79[a]	1081.03[a]	3251.55[a]
M2K2	223.59[a]	841.36[a]	1076.82[a]	3315.82[a]
M2K1	213.36[a]	808.36[a]	1076.59[a]	3295.31[a]

M0K2: 0 kg/ha $MgSO_4$, 414 kg/ha K_2O; M1K2: 45 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K2: 90 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K1: 90 kg/ha $MgSO_4$, 234 kg/ha K_2O.
Different letters indicated that the difference was significant at $P < 0.05$.

and 33.24% under M1K2, M2K2 and M2K1 treatments, respectively, compared with that of M0K2.

The results in Table 8 show that there was no difference in K and Mg uptake of tomato roots, stems, leaves and Ca uptake of tomato roots and leaves among the treatments as supply of Mg increased.

There was no difference in the uptake of K by tomato roots, stems and leaves as supply of Mg increased among treatments. When the supply of K decreased by 43.48%, the uptake of K decreased in tomato aboveground parts (16.75%), such as the stems (18.33%), leaves (7.75%) and fruit (21.51%) when M2K1 was compared with M2K2.

The uptake of total Ca by tomato aboveground parts, such as the stems, leaves and fruit increased as supply of Mg increased. The uptake of Ca by tomato aboveground parts in the total plant was the highest under M2K2 treatment and was significantly higher than those under M0K2, M2K2 and M2K1 treatments. The uptake of Ca by tomato decreased as supply of K decreased.

The uptake of Mg by tomato fruit increased significantly by 31.72, 100 and 36.21% under M1K2, M2K2 and M2K1 treatments, respectively, compared with that of M0K2 treatment. There was no significant difference in the uptake of Mg by tomato roots, stems and leaves among the four treatments.

4. Discussion

Magnesium affected by the potassium–calcium antagonistic interaction under a deficiency of magnesium in tomato

The yield and content of K, Ca and Mg were reduced because of Mg deficiency, which is similar to the results of other research. It was reported that the initial physiological response of Mg deficiency for plants was the accumulation of carbohydrates in leaves, and the suppression of supply of carbohydrates to roots (Cakmak, 2013; Farhat and Bouraoui, 2013), which affected root growth and nutrient absorption (Cakmak and Kirkby, 2008). An Mg deficiency may induce an imbalance of active oxygen metabolism in plants by suppressing photosynthetic carbon assimilation and causing a decrease in yield (Cakmak and Kirkby, 2008).

In this study, the contents of soil Mg with ND, MD, SD were 2.25, 2.31 and 2.05 cmol/kg, respectively. The content of soil Mg was four times greater than the established Mg deficiency threshold of Chinese soil (0.5 cmol/kg) (Yuan, 1983). It is clear that there was no deficiency of Mg in the first 3–5 years before experiment. One could hypothesize that calcareous soil could provide enough Mg nutrients for plant growth. A lack of application of Mg was not the reason for Mg deficiency.

The soil exchangeable K and $CSRK^+$ increased, and the soil exchangeable Mg and CSR Mg^{2+} decreased as the deficiency of Mg became more serious. Similar results were described by Chen *et al.* (2013). $CSRK^+$ with ND and MD was 7.68% and 9.35% lower, respectively, and $CSRMg^{2+}$ with ND and MD was 10.66% and 10.61% greater, respectively, compared with SD. White (2006) has proved that the appropriate ratio of cation saturation in soil colloids should be 80% of Ca^{2+}, 15% of Mg^{2+} and 5% of other cations such as K^+, Na^+ and NH_4^+. As compared with ND, the soil $CSRK^+$ under a deficiency of Mg was much higher, and the $CSRMg^{2+}$ was much lower. The changes might be caused primarily by the change in soil exchangeable K.

The soil K/Mg with ND, MD and SD was 0.72, 0.88 and 1.35, respectively. The soil K/Mg with MD and SD was 22.22% and 87.50% higher, respectively, than that with ND.

Table7. K, Ca, Mg contents of tomato at different treatments (cmol/kg).

Nutrient	Treatment	Root	Stem	Upper leaves	Lower leaves	Fruits
K	Mg0K2	53.72[a]	71.71[b]	79.53[ab]	71.49[a]	109.45[a]
	Mg1K2	47.24[a]	81.22[a]	88.62[a]	59.24[b]	101.30[a]
	Mg2K2	48.39[a]	80.78[a]	88.87[a]	59.73[b]	107.24[a]
	Mg2K1	53.89[a]	68.55[b]	75.44[b]	55.61[b]	84.65[b]
Ca	Mg0K2	192.64[a]	199.11[b]	358.2[a]	380.27[a]	18.71[d]
	Mg1K2	155.42[b]	206.05[ab]	294.63[b]	380.32[a]	20.54[c]
	Mg2K2	167.2[b]	240.37[a]	316.74[b]	401.87[a]	28.90[a]
	Mg2K1	170.6[ab]	227.63[ab]	357.4[a]	339.96[b]	25.28[b]
Mg	Mg0K2	17.29[a]	29.24[a]	11.11[a]	24.78[a]	3.73[b]
	Mg1K2	15.63[a]	28.26[a]	10.76[a]	22.48[a]	4.88[b]
	Mg2K2	15.39[a]	31.67[a]	12.51[a]	24.04[a]	7.25[a]
	Mg2K1	15.32[a]	29.34[a]	13.78[a]	23.77[a]	4.97[b]

M0K2: 0 kg/ha $MgSO_4$, 414 kg/ha K_2O; M1K2: 45 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K2: 90 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K1: 90 kg/ha $MgSO_4$, 234 kg/ha K_2O.
Different letters indicated that the difference was significant at $P < 0.05$.

Table 8. K, Ca and Mg uptake of tomato in different treatments (kg/ha).

Nutrient	Treatments	Roots	Stems	Leaves	Fruits	Aboveground	Total
K	M0K2	5.19[a]	22.37[ab]	31.36[a]	136.67[a]	190.40[a]	195.59[a]
	M1K2	3.49[a]	26.48[a]	26.58[ab]	128.01[ab]	181.06[a]	184.55[a]
	M2K2	4.25[a]	26.51[a]	27.09[ab]	138.12[a]	191.72[a]	195.97[a]
	M2K1	4.56[a]	21.65[b]	24.99[b]	108.41[b]	159.61[b]	159.61[b]
Ca	M0K2	9.19[a]	31.81[b]	85.41[ab]	11.79[c]	129.19[b]	138.39[b]
	M1K2	5.86[a]	34.54[b]	87.31[ab]	13.31[c]	135.16[b]	141.01[b]
	M2K2	7.47[a]	40.36[a]	92.77[a]	19.06[a]	152.19[a]	159.66[a]
	M2K1	7.39[a]	36.49[ab]	78.59[b]	16.60[b]	131.68[b]	139.06[b]
Mg	M0K2	1.03[a]	5.67[a]	6.78[a]	2.90[c]	15.35[b]	16.38[b]
	M1K2	0.72[a]	5.75[a]	6.26[a]	3.82[b]	15.83[b]	16.55[b]
	M2K2	0.83[a]	6.44[a]	6.73[a]	5.80[a]	18.97[a]	19.80[a]
	M2K1	0.80[a]	5.77[a]	6.70[a]	3.95[b]	16.42[ab]	17.22[ab]

M0K2: 0 kg/ha $MgSO_4$, 414 kg/ha K_2O; M1K2: 45 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K2: 90 kg/ha $MgSO_4$, 414 kg/ha K_2O; M2K1: 90 kg/ha $MgSO_4$, 234 kg/ha K_2O.
Different letters indicated that the difference was significant at $P < 0.05$.

It was reported that when the K/Mg ratio was more than 0.4~0.7 (Chapman, 1966; Kochian, 1995), the K will significantly inhibit absorption of Mg, which confirms the results of this study. The soil K/Mg without a deficiency in Mg was closer to the limit value, and the soil K/Mg with MD and SD was much higher than the limit value. The soil Ca/Mg with ND, MD and SD was 7.66, 7.55 and 8.98, respectively. Those were all larger than the limit values (<7.0) provided by Chapman (1966). The results described above indicate that Ca was one of the reasons for deficiency of Mg.

The contents of K, Ca and Mg in leaves and yield of tomato were negatively correlated with soil exchangeable K, CSRK^{+} and K/Mg but positively correlated with CSRCa^{2+}and Ca/K. Since soil exchangeable Ca and Mg changed so little, we can be confident of the result: the deficiency of Mg was caused by an increase in K. The increase in the content of soil K could affect the imbalance of ion ratio and induce deficiency in Mg and reduction in yield (Cakmak, 2013; Cakmak and Kirkby, 2008; Mengel and Kirkby, 2001; Römheld and Kirkby, 2007; White, 2006). Farmers provided much more K fertiliser for tomato with Mg deficiency, which was not necessary according to the research done of Miller and Donahue (1995). Their research showed that the appropriate available K for vegetables was 150–250 mg/kg. The available K was 295.50 mg/kg in this study. The antagonism between K^+ and Mg^{2+} is related to their similar chemical properties (Viadé *et al*. 2011). It was reported that some Mg transporters might also transport K. Hence, a high availability of K in the soil/rhizosphere blocks these nonspecific Mg transporters for Mg uptake (Gransee and Führs, 2013). However, there were studies that showed that cations, such as H^+, Na^+, NH_4^+ and Al^{3+}, could also affect the absorption of Mg (Mengel and Kirkvy, 2001). Additional studies should be conducted to focus on the mechanism and correction of Mg deficiency in calcareous soils.

The corrective effect of supply of magnesium and decrease of potassium on soil chemical properties, tomato yield and nutrient uptake

Supplying Mg and decreasing K did not correct the Mg deficiency of tomato. The results were the same as those identified by Wang *et al*. (2017). Supplying Mg and decreasing K caused a decrease in the soil K/Mg. The K/Mg of soil in M0K2, M1K2, M2K2 and M2K1 was 1.24, 1.06, 0.91 and 0.72, respectively. However, the soil K/Mg was larger than the limit of Mg deficiency as described previously (Chapman, 1966; Kochian, 1995). Hence, the Mg deficiency was observed in every treatment. The soil K/Mg was the lowest under M2K1 treatment, indicating that reducing the application of K was a quick way to restore cation balance.

In this study, the dry matter of tomato fruit increased by 1.19% and 3.19% with 45 kg/ha $MgSO_4$ and 90 kg/ha $MgSO_4$ supplied by topdressing, respectively. Wang *et al*. (2017) found that the yield was improved by 8.0, 8.9 and 5.3% when 0.2% $MgSO_4 \cdot 7H_2O$, 0.4% $MgSO_4 \cdot 7H_2O$ and 0.2% $Mg(NO_3)_2 \cdot 6H_2O$ were supplied by foliar sprays, respectively. The difference could be caused by the manner in which Mg fertiliser was supplied. Foliar spraying could be a more effective mode to supply fertiliser for tomato growth.

The differences in K, Ca and Mg contents and uptake were primarily observed in tomato fruit. The content and uptake of Ca and Mg increased as supply of Mg increased significantly, and the content and uptake of K, Ca and Mg decreased as supply of K decreased. There was no significant difference in the content and uptake of Mg by tomato leaves among the four treatments. Perhaps the transport of Mg from leaves to fruit was one of the reasons that supplying Mg and decreasing K supply was not effective at correcting deficiency of Mg. In addition, Wang *et al.* (2017) observed the same results. The content of Mg in tomato leaves decreased by 17.4–35.1% with tomato fruit growth.

5. Conclusions

A deficiency in Mg had a negative influence on tomato growth. The yield of tomatoes decreased significantly by 38.02% and 59.53% with MD and SD, respectively, compared with that of ND. The increase in content of soil K that caused an imbalance in ion ratio was the main reason for Mg deficiency of tomato in calcareous soil. The amount of soil exchangeable K, $CSRK^+$ and K/Mg increased, and the soil exchangeable Mg and CSR Mg^{2+} decreased as deficiency of Mg grew more serious. The K/Mg was higher than the limit value of Mg deficiency. Supplying Mg and decreasing the supply of K did not correct Mg deficiency of tomato during the first year. However, the yield of tomatoes increased, and the K/Mg of soil decreased as supply of Mg increased. Additional studies should be conducted to verify these results. The soil K/Mg under M2K1 treatment was the lowest (0.72) among treatments and could provide enough nutrition for tomato growth, indicating that a reduction in the supply of K while supplying Mg was a much more efficient way to decrease the soil K/Mg and restore cation imbalance than providing Mg fertiliser in calcareous soil.

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Conflict of interest

The authors have declared no conflict of interest in this article.

Compliance with ethical standards

This article followed all ethical standards for a research without direct contact with human or animal subjects.

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