Research Article

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Growth, chlorophyll content and productivity responses of maize to magnesium sulphate application in calcareous soil

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Abstract: Magnesium (Mg) is an essential plant macronutrient responsible for modulating many physiological or biochemical processes such as photosynthetic activity, amino acid synthesis and nucleotide metabolism. Agricultural soils with a more-than-adequate availability of calcium (Ca) have inherent Mg deficiency, potentially resulting in overall reduced soil productivity and crop yield potential. We conducted a field experiment to investigate the optimum soil application of Mg to increase crop growth and productivity under calcareous soil conditions. In addition to recommended soil application of mineral fertilizers, we applied the following four levels of Mg to the soil in the form of anhydrous MgSO4: control, 4 kg Mg ha$^{-1}$ (Mg4), 8 kg Mg ha$^{-1}$ (Mg8) and 16 kg Mg ha$^{-1}$ (Mg16). Results showed that Mg16 application enhanced the plant height (21%), number of grains (18%), 1,000 grains weight (20%), grain yield (20%) and biological yield (9%) over control ($p \leq 0.05$). Chlorophyll $a$, chlorophyll $b$ and total chlorophyll were generally higher at the Mg8 and Mg16 levels than at the control level. Contrasting to increases in growth traits, the concentration of K significantly decreased in grains, leaves and shoots of maize along the soil’s Mg gradient ($p \leq 0.05$). We suggest that Mg16 overcomes the deficiency of soil Mg and can increase the crop yield traits in calcareous soils. More investigations of the effect of soil Mg on various crops grown in calcareous soils may add to our knowledge related to the stressing impact of soil Mg on plant K concentration.

Keywords: chlorophyll, magnesium, maize, nutrients concentration, yield

1 Introduction

Magnesium (Mg) is a proportionately important macronutrient essential for plant growth and is the eighth major plentiful mineral element on earth (Maguire and Cowan 2002). Occupying the central location in chlorophyll structure, it is integral to modulating many physiological and biochemical processes including the activation of more than 300 plant growth enzymes such as carboxylases, kinases, phosphatases, ATPases and RNA polymerases (Mengel et al. 2001; Cakmak and Kirkby 2008; Hawkesford et al. 2012). About three-quarters of leaf Mg content appears to be associated with amino acid and protein synthesis, up to one-fifth with chlorophyll pigments, and the remaining fraction is stored in the vacuole (Karley and White 2009). More importantly, three major macronutrients (carbon, nitrogen and sulphur) translocated by the roots are further assimilated in the presence of Mg (Marschner and Rengel 2012).

Different kinds of silicates and fertilizers extracted from rocks are the major sources of Mg in agricultural soils. Mobility of Mg in soil is known to be controlled by its soil concentration, soil moisture content and soil temperature
(Gransee and Führs 2013). The divalent ion (Mg\(^{2+}\)) exists as exchangeable and nonexchangeable forms in clay or organic matter and as available form in soil solution. The available form is transported from rhizosphere to plant parts by mass flow of water (Lynch and Clair 2004), and therefore, its uptake is very low in dry soils.

For healthy crop production, the required Mg concentration in the vegetative tissues (dry weight basis) should be in a range of 1.5–3.5 mg g\(^{-1}\) (Hawkesford et al. 2012), while that in soil solution is mostly between 125 μmol L\(^{-1}\) and 8.5 mmol L\(^{-1}\) (Karley and White 2009; Marschner and Rengel 2012). Deficiency occurred in acidic, calcareous, saline and sodic soils due to excessive aluminium or manganese (Mengel et al. 2001; Gransee and Führs 2013). In high pH soils, MgCO\(_3\) formation and excess calcium, potassium and sodium contents may decrease Mg availability to crops (Broadley and White 2010). A low concentration of Mg in weathering material used for fertilizer manufacturing is also a major cause of Mg deficiency (El-Dissoky et al. 2017). Generally, for the high production agricultural systems, the rate of NPK fertilization is usually increased, which raises the risk of Mg deficiency because soil Mg has a reciprocal impact on plant K concentration (Guiet-Bara et al. 2007; Han et al. 2019). Intensive cultivation of crops without the use of Mg fertilization also contributes to an increase in Mg stress in soils and plants (Grzebisz 2011). It is reported that deficiency symptoms of Mg become quite prominent below 1–2 mg g\(^{-1}\) Mg in dry leaves (Hermans et al. 2010; Verbruggen and Hermans 2013).

The productivity and quality of crops are significantly impacted by Mg nutritional disorder in agriculture, horticulture (Ruan et al. 2010; Mengutay et al. 2013; Hauer-Jákli and Tränkner 2019) and forestry practices (Huang et al. 2010; Grzebisz 2011). The toxicity of Mg is also reported in several plants (Hawkesford et al. 2012) in semi-arid regions or in soil with high Mg-to-Ca ratio (Chen et al. 2018), although Mg toxicity symptoms are mostly hidden in plants even at its high concentration (Farhat et al. 2016). Major Mg deficiency symptoms include patches on leaf marginal veins (Guo et al. 2015) and necrosis spots on leaves.

In addition to many known critical uses of maize (Zea mays L.), such as human food (cereal) and animal food (silage and poultry feed), the crop is being used increasingly for the production of biofuel (ethanol) to reduce carbon footprint intensity in the face of climate change (Munir et al. 2015). While most of the essential macro- and micronutrients are extensively investigated for their optimum uses and crop yields, inquiries into the uses of Mg for optimizing soil productivity and crop yield potential in calcareous soils remained mostly unexplored. We hypothesize that the addition of Mg will mitigate Mg deficiency under calcareous soil conditions and optimize maize crop yield traits. Therefore, the current study was conducted with the objective to examine the influence of soil application of Mg on maize growth and productivity in calcareous soils.

## 2 Materials and methods

### 2.1 Experimental site and treatment plan

A field study was conducted in the experimental agricultural area (30°16′40″N, 71°30′79″E) of Bahauddin Zakariya University, Multan, Pakistan. Monthly averages of the meteorological data collected during the experiment is provided in Figure 1. Four treatments with three replicates \((4 \times 3 = 12\) plots; each plot size \(= 10 \text{ m}^2\)) were arranged in a randomized complete block design. The treatments included control (no Mg application), Mg4 (4 kg Mg ha\(^{-1}\)), Mg8 (8 kg Mg ha\(^{-1}\)) and Mg16 (16 kg Mg ha\(^{-1}\)).

### 2.2 Soil characterization

Experimental soil was characterized as arid (recent flood plain of the Indus delta), porous, friable and deep. The soil was weakly structured, moderately calcareous (CaCO\(_3\); 51 g kg\(^{-1}\)), brown to dark yellowish-brown, and well-drained with Ochric epipedon and cambic subsurface horizon (mixed hyperthermic Fluventic Haplocambids, Sultanpur Series). A soil–water ratio (1:1 ratio) was used for soil pH analysis using a Jenway 3,510 pH meter. A soil–water ratio of 1:10 was used to measure soil ECe

![Month: July | August | September | October](chart)

**Figure 1:** Monthly averages of the meteorological data collected during the experiment.
(Bante DDS-12DW microprocessor-based EC meter). We employed the hydrometer method and determined soil texture to be a silt loam (Gee and Bauder 1986). Analysis of soil organic matter was performed as described by Walkley (1935). Organic nitrogen in the soil was assessed by using the equation of United State Salinity Laboratory Staff (1954):

\[ \text{Organic N (\%)} = \frac{\text{Soil organic matter}}{20} \]

The methodology of Sommers and Olson (1985) was followed for P determination in soil on a spectrophotometer (Hitachi U-2000). Jones's (1998) method was adopted for extractable K analysis in soil using a PFP-7 flame photometer (Table 1).

### 2.3 Fertilization and irrigation

All plots were prepared after completing regionally recommended tillage operations (1 rotavator, 4–5 cultivator). Macronutrients (N, P and K) were applied to the soil at the rate of 120 kg N, 90 kg P_2O_5 and 60 kg K_2O ha\(^{-1}\) in all the treatments and were sourced from urea, diammonium phosphate and potassium sulphate, respectively (Ahmad et al. 2018). Nitrogen was applied in three splits while all P and K fertilizers were applied at the time of sowing. Maize was watered using a total of 10 irrigations amounting to an approximate total water depth of 600 mm.

### 2.4 Harvesting and growth attributes

For chlorophyll content, harvesting was done at vegetative maturity. Fresh leaves were collected randomly from treatment and composite sample was used for analyses of chlorophyll. Maize was harvested at the full maturity stage and immediately subjected to the determination of growth attributes: plant height and fresh and dry weights. From 1 m\(^2\) area of each plot, plants were harvested, and fresh weight was assessed on a weighing balance. After fresh weight, plant samples were dried in an oven at 65°C for 24 h. Finally, dry weight was precisely measured on a weighing balance.

### 2.5 Yield attributes

Ten randomly selected cobs were taken, and the number of grains and grain rows were counted manually. Weight of 1,000 grains and grain yield were measured on a weight balance. Harvested plants were weighed (to get biological yield), dried (to remove moisture) and weighed again to record yield on a dry weight basis. Harvesting index was calculated by using the equation:

\[ \text{Harvesting index (\%)} = \frac{\text{Grains yield (t ha}^{-1}\text{)}}{\text{Biological yield (t ha}^{-1}\text{)}} \times 100. \]

### 2.6 Chlorophyll contents

A 0.5 g composite sample of mature fresh leaves was crushed in 10 mL (80%) of acetone. The crushed sample was filtered, and then the final desired volume was achieved using acetone (80%). Finally, we observed the absorbance at 645 and 663 nm wavelengths on a spectrophotometer. Chlorophyll contents were calculated by using the following equations:

**Chlorophyll a (mg g\(^{-1}\) F.W.)**

\[ = \frac{12.7(\text{OD 665}) - 2.69(\text{OD 645})}{1,000 \times W} \]

**Chlorophyll b (mg g\(^{-1}\) F.W.)**

\[ = \frac{22.9(\text{OD 645}) - 4.68(\text{OD 663})}{1,000 \times W} \]

**Total chlorophyll (mg g\(^{-1}\) F.W.) = chlorophyll a + chlorophyll b**

where OD = optical density (nm), V = final volume made (mL) and F.W. = fresh weight of leaves (g).

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### Table 1: Pre-experimental characteristics of the soil

| Soil     | Unit | Value |
|----------|------|-------|
| Sand     | %    | 29    |
| Silt     | %    | 63    |
| Clay     | %    | 8     |
| Texture  | Silt loam |  | 
| pH_s     | —    | 8.31  |
| EC_e     | dS m\(^{-1}\) | 1.24 |
| Organic matter | % | 0.60 |
| Extractable P | µg g\(^{-1}\) | 5.39 |
| Extractable K | µg g\(^{-1}\) | 175 |

pH_s = pH of soil saturated paste (1:1). EC_e = EC of soil extract (1:10).
2.7 Nutrients analyses

Grain, leaf and shoot samples were digested using H$_2$SO$_4$, and total N was determined using a Kjeldahl’s distillation apparatus, with 4% boric acid as collecting solution (Van Schouwenberg and Walinge 1973). Dil–acid (HNO$_3$:HClO$_4$) mixture was used for the digestion of grain, leaf and shoot samples for the analyses of P, K and Mg. For P, ammonium heptamolybdate and malachite green were used. Absorbance was noted at 610 nm wavelength on a spectrophotometer (Hitachi U-2000) by following the study of Motomizu et al. (1984). Digested samples were run on a flame photometer (PFP-7) and an atomic absorption spectrophotometer (PerkinElmer, Analyst 100, Waltham, USA) for the determination of K and Mg, respectively. For the determination of protein contents in grains, N (%) was multiplied with a constant factor 6.25 as described by Hiller et al. (1948).

2.8 Statistical analysis

A standard statistical procedure was used for the statistical analysis of data. One-way analysis of variance was applied for significance determination. For comparison of each treatment, Tukey’s test at the 5% level of significance was applied.

3 Results

3.1 Growth and yield attributes

Different levels of Mg application in soil significantly ($p \leq 0.05$) affect the growth and yield of maize cultivated in calcareous soil. The height of maize plants and the number of grains were significantly the highest when Mg16 was applied. It was observed that Mg8 differed significantly over Mg4 and control for plant height and the number of grains. Maximum enhancement of 21% and 18% in plant height and number of grains were noted, respectively, where Mg16 was applied over control.

3.2 Grains weight, yield and harvesting index

In the case of 1,000 grains weight, Mg16 performed best over all other treatments. No significant change was noted among Mg4 and Mg8 for 1,000 grains weight. However, both Mg8 and Mg4 differed significantly for 1,000 grains weight over control. A maximum enhancement of 20% in 1,000 grains weight was observed when Mg16 was applied over control. For grain, dry and biological yields, Mg16 remained significantly over Mg4 and control. In the case of grains yield, Mg16 and Mg8 were the same, while in biological yield Mg8 and Mg4 were statistically similar to each other (Table 2). A maximum enhancement of 20, 43 and 9% in grain, dry matter and biological yields were noted, respectively, where Mg16 was applied over control. In the case of harvesting index, Mg16 and Mg8 were the same but differed significantly over Mg4 and control. A maximum increase of 11% in 1,000 grains weight was observed when Mg16 was applied over control.

3.3 Nutrient concentration in grains and shoot

Different levels of Mg application in soil significantly ($p \leq 0.05$) affect the concentration of nutrients in grains and shoots of maize cultivated in calcareous soil. Application of Mg16 and Mg8 significantly increased N in grains compared to the Mg4 and control treatments (Table 3). No significant changes were noted among Mg16, Mg8 and Mg4, but all levels of Mg differed significantly over control for P concentration in maize grains. It was observed that the increasing level of Mg reduced the K concentration in maize grains. Increasing soil application of Mg increased its concentration in grains. A maximum enhancement of 0.48-, 0.50-, 2.6-fold in N, P and Mg concentrations in maize grains was observed where Mg16 was applied over control. However, the application of Mg16 caused a significant reduction of 0.32-fold in the K concentration of maize grains. In the case of N, P and Mg concentrations in shoots, a similar trend of enhancement with an increase in the application rate of Mg was noted. Application of Mg16 gave a maximum enhancement of 0.62-, 0.23- and 3.3-fold in N, P and Mg concentrations in maize shoot over control. However, the application of Mg16 caused a significant reduction of 0.33-fold in the K concentration in maize shoot.

3.4 Nutrient concentration in soil and leaves

Different levels of Mg application in soil significantly ($p \leq 0.05$) affected the concentrations of the nutrients in soil and leaves of maize. It was observed that N, P and Mg
concentrations in leaves and soil were increased by increasing the application rate of Mg (Table 4). Application of Mg8 and Mg4 were statistically similar for P concentration in maize leaves, but Mg8 remained significantly better over Mg4 for the available P in soil. However, the application of Mg16 caused a significant reduction in K concentration in leaves and extractable K in the soil. Application of Mg16 gave a maximum enhancement of 0.64-, 0.23- and 1.9-fold in N, P and Mg concentrations in maize leaves over control. However, Mg16 caused a significant decrease of 0.30- and 0.56-fold K concentration in leaves and 0.56-fold extractable K in the soil.

### 3.5 Chlorophyll content and grains protein

Different levels of Mg application in soil significantly ($p \leq 0.05$) affected chlorophyll content in leaves and protein content of maize grains. It was noted that the application of Mg8 and Mg16 remained statistically similar for chlorophyll $a$, chlorophyll $b$ and total chlorophyll in maize leaves (Figure 2a–c). Application of Mg4 and Mg8 did not differ significantly for chlorophyll $a$ but differed significantly for chlorophyll $b$ and total chlorophyll in maize. However, increasing the level of Mg significantly increased chlorophyll $a$, chlorophyll $b$ and total chlorophyll in maize leaves over control. Maximum enhancements in chlorophyll $a$ (1.14-fold), chlorophyll $b$ (1.04-fold) and total chlorophyll (1.10-fold) were noted when Mg16 was applied as an amendment over control. For protein contents in grains, Mg16 remained the best among all the treatments (Figure 3). The maximum increase of 47% in protein content in grains was observed in Mg16 over control.

### 4 Discussion

In the current study, plant height and dry matter were improved over control (no Mg was applied) by increasing the application of Mg in soil. This enhancement in plant height and dry biomass by the addition of Mg has also been frequently documented (Sabo et al. 2002). Better uptake of phosphorus, improvement in photosynthesis, sugar contents and translocation of starch due to the uptake of Mg play a crucial role in a significant increase of dry biomass and plant height (Marschner and Rengel 2012). However, in the current study, Mg concentration in grains, leaves and shoots was observed to be quite low...
Table 3: Maize grains and shoot nutrients concentration under various levels of Mg in calcareous soils

| Treatment | Nutrient concentration of the grains |  |  |  |
|-----------|-------------------------------------|---|---|---|
|           | Nitrogen (%): Phosphorus (%): Potassium (%): Magnesium mg g\(^{-1}\) |  |  |  |
| Control   | 0.90 ± 0.015\(^b\): 0.16 ± 0.003\(^c\): 1.68 ± 0.042\(^a\): 1.55 ± 0.29\(^d\) |  |  |  |
| Mg4       | 1.10 ± 0.057\(^b\): 0.18 ± 0.003\(^b\): 1.39 ± 0.015\(^b\): 2.72 ± 0.04\(^c\) |  |  |  |
| Mg8       | 1.25 ± 0.019\(^a\): 0.22 ± 0.004\(^a\): 1.22 ± 0.015\(^c\): 3.90 ± 0.27\(^b\) |  |  |  |
| Mg16      | 1.33 ± 0.010\(^a\): 0.24 ± 0.001\(^a\): 1.15 ± 0.022\(^c\): 5.58 ± 0.41\(^a\) |  |  |  |

| Treatment | Nutrient concentration in the shoots |  |  |  |
|-----------|-------------------------------------|---|---|---|
|           | Nitrogen (%): Phosphorus (%): Potassium (%): Magnesium mg g\(^{-1}\) |  |  |  |
| Control   | 0.76 ± 0.026\(^b\): 0.13 ± 0.008\(^c\): 2.06 ± 0.032\(^a\): 1.45 ± 0.03\(^d\) |  |  |  |
| Mg4       | 0.92 ± 0.021\(^c\): 0.15 ± 0.001\(^b\): 1.83 ± 0.017\(^b\): 3.08 ± 0.05\(^c\) |  |  |  |
| Mg8       | 1.14 ± 0.024\(^b\): 0.15 ± 0.001\(^b\): 1.51 ± 0.023\(^c\): 5.15 ± 0.27\(^b\) |  |  |  |
| Mg16      | 1.23 ± 0.021\(^a\): 0.16 ± 0.001\(^a\): 1.37 ± 0.023\(^b\): 6.21 ± 0.21\(^a\) |  |  |  |

Mean ± standard error of three replicates having different letters in a column show a significant difference at \(p \leq 0.05\) (Tukey’s test). Mg4 = Mg 4 kg ha\(^{-1}\), Mg8 = Mg 8 kg ha\(^{-1}\) and Mg16 = Mg 16 kg ha\(^{-1}\).

Table 4: Maize leaves and soil nutrient concentration under various levels of Mg in calcareous soils

| Treatment | Nutrients concentration in leaves |  |  |  |
|-----------|----------------------------------|---|---|---|
|           | Nitrogen (%): Phosphorus (%): Potassium (%): Magnesium mg g\(^{-1}\) |  |  |  |
| Control   | 0.91 ± 0.015\(^b\): 0.26 ± 0.0035\(^c\): 2.00 ± 0.015\(^a\): 2.13 ± 0.41\(^c\) |  |  |  |
| Mg4       | 1.15 ± 0.026\(^c\): 0.29 ± 0.0032\(^b\): 1.78 ± 0.017\(^b\): 3.45 ± 0.41\(^c\) |  |  |  |
| Mg8       | 1.32 ± 0.003\(^b\): 0.30 ± 0.0033\(^b\): 1.57 ± 0.036\(^c\): 4.68 ± 0.34\(^b\) |  |  |  |
| Mg16      | 1.49 ± 0.012\(^a\): 0.32 ± 0.0000\(^a\): 1.40 ± 0.006\(^b\): 6.10 ± 0.42\(^a\) |  |  |  |

| Treatment | Nutrient concentration of the soil |  |  |  |
|-----------|----------------------------------|---|---|---|
|           | Nitrogen: Phosphorus: Potassium: Magnesium mg kg\(^{-1}\) |  |  |  |
| Control   | 0.020 ± 0.0001\(^d\): 6.43 ± 0.003\(^b\): 290 ± 11.5\(^a\): 28.3 ± 0.77\(^d\) |  |  |  |
| Mg4       | 0.034 ± 0.0009\(^c\): 8.11 ± 0.005\(^c\): 223 ± 16.5\(^b\): 39.1 ± 1.99\(^c\) |  |  |  |
| Mg8       | 0.048 ± 0.0004\(^b\): 9.92 ± 0.005\(^b\): 183 ± 8.82\(^c\): 49.0 ± 1.44\(^b\) |  |  |  |
| Mg16      | 0.051 ± 0.0003\(^a\): 12.3 ± 0.002\(^a\): 127 ± 8.82\(^b\): 60.9 ± 1.83\(^a\) |  |  |  |

Mean ± standard error of three replicates having different letters in a column show a significant difference at \(p \leq 0.05\) (Tukey’s test). Mg4 = Mg 4 kg ha\(^{-1}\), Mg8 = Mg 8 kg ha\(^{-1}\) and Mg16 = Mg 16 kg ha\(^{-1}\).

Figure 2: Chlorophyll contents (chlorophyll a = (a), chlorophyll b (b) and total chlorophyll (c)) in maize cultivated under various levels of Mg in calcareous soils. Red bar indicates minimum, orange bar indicates medium and green bar indicates the maximum synthesis of chlorophyll.
that catalyses the first major step of carbon fixation (Wu et al. 2012). Limited uptake of Mg affects the net rate of photosynthesis across a wide variety of plant species (Hariadi and Shabala 2004; Shabala and Hariadi 2005; Tang et al. 2012). In the current study, increasing application of Mg improved chlorophyll a, chlorophyll b and total chlorophyll in maize under calcareous soil conditions. According to Marschner and Rengel (2012), Mg acts as a cofactor and an allosteric activator of enzymes that are involved in CO2 fixation and transfer of energy through adenosine triphosphate.

5 Conclusion

Increasing soil application of Mg increased maize yield traits but reduced K concentration in leaves, grains and shoots, which is a major concern when Mg is used as an amendment in calcareous soil. Therefore, only an optimum or a lesser dose of Mg may be applied to maize crop grown in calcareous soil. Further investigations on soil Mg across various crops grown in calcareous soils may add to our knowledge related to the stressing impact of soil Mg on plant K concentration.

Conflict of interest: The authors declare no conflict of interest.

References

[1] Ahmad I, Bibi F, Ullah H, Munir TM. Mango fruit yield and critical quality parameters respond to foliar and soil applications of zinc and boron. Plants. 2018;7:97.
[2] Broadley MR, White PJ. Eats roots and leaves. Can edible horticultural crops address dietary calcium, magnesium and potassium deficiencies? Proc Nutr Soc. 2010;69:601–12.
[3] Cakmak I, Kirkby EA. Role of magnesium in carbon partitioning and alleviating photooxidative damage. Physiol Plant. 2008;133:692–704.
[4] Chen ZC, Peng WT, Li J, Liao H. Functional dissection and transport mechanism of magnesium in plants. Semin Cell Dev Bio. 2018;74:142–52.
[5] El-Dissoky RA, Al-Kamar FA, Derar RM. Impact of magnesium fertilization on yield and nutrients uptake by maize grown on two different soils. Egypt J Soil Sci. 2017;57:455–66.
[6] Farhat N, Elkhouni A, Zorrig W, Smouei A, Abdelly C, Rabhi M. Effects of magnesium deficiency on photosynthesis and carbohydrate partitioning. Acta Physiol Plant. 2016;38:145.
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[7] Gee GW, Bauder JW. Particle-size analysis. In: Klute A, editor. Methods of soil analysis. Part 1 Physical and mineralogical methods, Chap. 15. American Society of Agronomy, and Soil Science Society of America; 1986. p. 383–411.

[8] Gerendás J, Führs H. The significance of magnesium for crop quality. Plant Soil. 2013;368:101–28.

[9] Gransee A, Führs H. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil. 2013;368:5–21.

[10] Grzебисz W. Magnesium – food and human health. J Elem. 2011;16:299–323.

[11] Guiet-Bara A, Durlach J, Bara M. Magnesium ions and ionic channels: Activation, inhibition or block – a hypothesis. Magnes Res. 2007;20:100–6.

[12] Guo W, Chen S, Hussain N, Cong Y, Liang Z, Chen K. Magnesium stress signaling in plant: just a beginning. Plant Signal Behav. 2015;10:e992287.

[13] Han T, Cai A, Liu K, Huang J, Wang B, Li D, et al. The links between potassium availability and soil exchangeable calcium, magnesium, and aluminum are mediated by lime in acidic soil. J Soils Sediment. 2019;19:1382–92.

[14] Hariadi Y, Shabala S. Screening broad beans (vicia faba) for magnesium deficiency. II. Photosynthetic performance and leaf bioelectrical responses. Funct Plant Biol. 2004;31:539–49.

[15] Hauer-Jäkl M, Tränkner M. Critical leaf magnesium thresholds and the impact of magnesium on plant growth and photo-oxidative defense: a systematic review and meta-analysis on 70 years of research. Front Plant Sci. 2019;10:766.

[16] Hawkesford M, Horst W, Kichey T, Lambers H, Schjoerring J, Møller IS, et al. Functions of macronutrients. In: Marschner P, editor. Marschner's mineral nutrition of higher plants. UK: Pergamon; 2012. p. 135–89

[17] Hermans C, Vuylsteke M, Coppens F, Cristescu SM, Harren Fj, Inzé D, et al. Systems analysis of the responses to long-term magnesium deficiency and restoration in Arabidopsis thaliana. N Phytol. 2010;187:132–44.

[18] Hiller A, Plazin J, Van Slyke DD. A study of conditions for kjeldahl determination of nitrogen in proteins description of methods with mercury as catalyst, and titrimetric and gasometric measurements of the ammonia formed. J Biol Chem. 1948;176:1401–20.

[19] Huang JL, Xu J, Ye X, Luo TY, Ren LH, Fan GC, et al. Magnesium deficiency affects secondary lignification of the vascular system in citrus sinensis seedlings. Trees. 2019;33:171–82.

[20] Jones JB. Soil test methods: past, present, and future use of soil extractants. Commun Soil Sci Plant Anal. 1998;29:1543–52.

[21] Kaftan D, Brumfeld V, Nevo R, Scherz A, Reich Z. From chloroplasts to photosystems: in situ scanning force microscopy on intact thylakoid membranes. EMBO J. 2002;21:6146–53.

[22] Karley AJ, White PJ. Moving cationic minerals to edible tissues: potassium, magnesium, calcium. Curr Opin Plant Biol. 2009;12:291–8.

[23] Lynch JP, Clair SBS. Mineral stress: the missing link in understanding how global climate change will affect plants in real world soils. Field Crop Res. 2004;90:101–15.

[24] Maguire ME, Cowan JA. Magnesium chemistry and biochemistry. Biometals. 2002;15:203–10.

[25] Marschner P, Rengel Z. Contributions of rhizosphere interactions to soil. In: Abbott LK, Murphy DV, editors. Soil biological fertility—a key to sustainable land use in agriculture. Dordrecht: Kluwer Academic Publishers; 2007. p. 81–98.

[26] Mengel K, Kirkby EA, Kosegarten H, Appel T. Nitrogen. Principles of plant nutrition. Dordrecht: Kluwer Academic Publishers; 2001. p. 397–434.

[27] Mengutay M, Ceylan Y, Kutman UB, Cakmak I. Adequate magnesium nutrition mitigates adverse effects of heat stress on maize and wheat. Plant Soil. 2013;368:57–72.

[28] Motomizu S, Wakimoto T, Töei K. Solvent extraction-spectrophotometric determination of phosphate with molybdate and malachite green in river water and sea-water. Talanta. 1984;31:235–40.

[29] Munir TM, Perkins M, Kaing E, Strack M. Carbon dioxide flux and net primary production of a boreal treed bog: responses to warming and water-table-lowering simulations of climate change. Biogeosci. 2015;12:1091–11.

[30] Papenbrock J, Grimm B. Regulatory network of tetrapyrrole biosynthesis – studies of intracellular signalling involved in metabolic and developmental control of plastids. Planta. 2001;213:667–81.

[31] Ruan J, Haerdter R, Gerendás J. Impact of nitrogen supply on carbon/nitrogen allocation: a case study on amino acids and catechins in green tea [camellia sinensis (L.) o. Kuntze] plants. Plant Biol. 2010;12:724–34.

[32] Sabo M, Teklic T, Vidovic I. Photosynthetic productivity of two winter wheat varieties (Triticum aestivum L.). Rost Vyroba. 2002;48:80–6.

[33] Shabala S, Hariadi Y. Effects of magnesium availability on the activity of plasma membrane ion transporters and light-induced responses from broad bean leaf mesophyll. Planta. 2005;221:56–65.

[34] Sommers AA, Olson SR. “Negative symptoms”: conceptual and methodological problems. Schizophr Bull 1985;11:364–79.

[35] Tang N, Li Y, Chen LS. Magnesium deficiency-induced impairment of photosynthesis in leaves of fruiting citrus reticulata trees accompanied by up-regulation of antioxidant metabolism to avoid photo-oxidative damage. J Plant Nutr Soil Sci 2012;175:784–93.

[36] Vacek S, Vacek Z, Ulbrichová I, Remes J, Podrázký V, Vach M, et al. The effects of fertilization on the health status, nutrition and growth of norway spruce forests with yellowing symptoms. Scand J For Res. 2019;34:267–81.

[37] Van Schouwenberg JCh, Walinge I. Methods of analysis for plant material. The Netherlands: Agric. Univ. Wageningen; 1973.

[38] Verbruggen N, Hermans C. Physiological and molecular responses to magnesium nutritional imbalance in plants. Plant Soil. 2013;368:87–99.

[39] Walkley A. An examination of methods for determining organic carbon and nitrogen in soils 1. J Agri Sci 1935;25:598–609.
[40] Wu Z, Zeng B, Li R, Song L. Combined effects of carbon and phosphorus levels on the invasive cyanobacterium, cylindrospermopsis raciborskii. Phycologia. 2012;51:144–50.

[41] Zhao H, Zhou Q, Zhou M, Li C, Gong X, Liu C, et al. Magnesium deficiency results in damage of nitrogen and carbon cross-talk of maize and improvement by cerium addition. Biol Trace Elem Res. 2012;148:102–9.