RESEARCH ARTICLE
doi: 10.2306/scienceasia1513-1874.2023.035

Response and efficiency of magnesium fertilizer application in soybean (*Glycine max*) and sunflower (*Helianthus annuus*)

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Received 16 Apr 2022, Accepted 11 Mar 2023
Available online

ABSTRACT: Magnesium (Mg) is essential in plant biochemical processes. However, tropical Ultisols soils generally contain low levels of Mg. Mg is often neglected in fertilization programs, and proper application rates have not yet been established. This study was designed to assess the influence of Mg application on soybean (*Glycine max*) and sunflower (*Helianthus annuus*) with regard to biomass accumulation, Mg efficiency traits, and the optimal accumulation ratio of K:Mg in the plant. A low extractable Mg (12.20 mg/kg) soil was used to evaluate the plant responses to Mg application at 0, 50, 100, and 200 mg Mg/kg in a pot experiment. The results showed that Mg fertilizer application at the 50 mg Mg/kg level improved biomass by 25% and 119% in soybean and sunflower, respectively, exhibiting a K:Mg accumulation ratio of 3:1 in plants. The Mg fertilizer application at 50–100 mg Mg/kg enhanced plant growth and nutrient uptake and elevated the leaf Mg concentration above the critical level. In contrast, excessive Mg fertilizer application (200 mg Mg/kg) suppressed biomass and nutrient accumulation. Therefore, a suitable Mg fertilizer application for optimum plant growth and high efficiency factors can be recommended at 50–100 mg Mg/kg for soybean and sunflower cultivated in tropical Ultisols soils containing low extractable Mg.

KEYWORDS: agronomic efficiency, K/Mg ratio, Mg fertilizer, nutrient use efficiency

INTRODUCTION

A low level of soil magnesium (Mg) has been identified as the primary cause of imbalanced plant nutrition that is detrimental to the yield and quality of the crop [1], and this condition emerges with Mg reduction in the soil profile [2]. Tropical soils are often highly leached acidic soils with low Mg, organic matter, and cation exchange capacity [3]. Thailand is located in the tropical zone, and over 40% of its soils are classified as Ultisols that contain low extractable Mg (Extr. Mg) [4]. Soil Mg deficiency is more common in coarse-textured soil than in fine-textured soil [5]. In tropical soils, low Mg content has been reported in soils used to cultivate banana (*Musa paradisiaca*) [6], rubber tree (*Hevea brasiliensis*) [7], and oil palm (*Elaeis guineensis*) [8], and in tropical natural forests [9]. In soils with low Extr. Mg content, kieserite ($MgSO_4$) and dolomite ($CaMgCO_3$) are recommended to enhance the soil Mg levels.

Plants have shown positive responses to Mg application when tested in soil with low Mg content, and this has been observed in fruits [10], vegetables [11], cereal crops [12], and perennial crops [13]. However, soybean (*Glycine max*) and sunflower (*Helianthus annuus*) are edible plants and sources of nutrition for humans and livestock, and the information regarding Mg fertilizer use for these crops is still limited.

The importance of Mg in plant growth necessitates the application of Mg fertilizer to cultivated soil and growing media with low Extr. Mg [14]. However, higher Mg fertilizer application rates may cause antagonism between Mg and potassium (K) in plant uptake, triggering reduced plant growth, as observed in citrus (*Citrus reticulata* Blanco cv. Kinokuni) [15], rice (*Oryza sativa*) [16], and longkong (*Lansium parasiticum*) [17], although the Mg and K levels in the soil were found to be sufficient. Therefore, information regarding the optimal ratio between K and Mg in cultivated soil must be established to avoid this condition.

Modern-day agriculture requires high production efficiency through improved plant productivity but at minimal costs of input materials. Nutrient use efficiency (NUE), nutrient accumulation efficiency (NUpE), and agronomic efficiency (AE) are some metrics used to estimate the efficiency of fertilizer application [18].

The objectives of this study were to 1) assess the responses in plant growth after Mg fertilizer application, 2) evaluate the efficiency of Mg application, 3) evaluate Mg uptake, and 4) estimate the optimal balance between Mg and K in the plant. This is the first reported combination study of Mg fertilizer application to evaluate the Mg fertilizer efficiency. This study will contribute to the development of precise guidelines for Mg fertilizer application to meet plant requirements, avoid the antagonism of Mg and K in plant growth, and establish high efficiency of Mg fertilizer application in agricultural practice.

MATERIALS AND METHODS

Soil sampling and treatment application

A low extractable Mg (12.20 mg/kg; 1 M NH_4OAc pH 7.0 extractant) Kho-hong (Kh) soil series (47N, X:467394, Y:786132), which is a coarse-loamy, kaolinitic, and isohyperthermic Typic Kandiudults was sampled at a depth of 0–30 cm. The soil was air-dried and sieved through a 10-mm plastic screen mesh for the pot experiments or through a 2-mm mesh for the physicochemical properties analysis. The soil was further passed through a 0.5-mm sieve for organic matter estimation.

Physicochemical properties analysis

The essential soil physicochemical properties analysis followed the standard method for soil analysis [5]. Soil pH was measured in a supernatant of 1:5 (w/v) soil:deionized water suspension. Organic matter (OM) was determined using the Walkley and Black method. The Bray II procedure was applied to establish the available phosphorus (Avail. P). Total nitrogen (total N) was evaluated using the Kjeldahl method. A 1 M NH_4OAc (pH 7.0) solution was used to estimate extractable Mg, K, and Ca (Extr. Mg, K, and Ca), while the soil texture assessment followed the pipette method. The physicochemical properties analysis of the Kh soil series showed that, by particle size distribution, the Kh soil series contained 76%, 16%, and 8% (w/w) of sand, silt, and clay, respectively, and was classified as sandy loam (Table 1). The soil fertility was generally poor, with a strongly acidic soil pH (4.73), low OM (27.82 g/kg) [19], and low Extr. Mg content (12.20 mg/kg) [20].

Pot cultivation

The pot cultivation study was conducted under complete randomized design with four replicates during September 2020 to March 2021 at the Prince of Songkla University in Thailand. Kieserite ($MgSO_4$) was applied at the rates of 0, 50, 100, and 200 mg Mg/kg. Composite soil samples were mixed thoroughly using an electric motor stirrer for different Mg application rates. Then, 5 kg of soil was placed into individual pots to cover four replicates from the primary composite sample. Four seeds of soybean (*Glycine max*; Chiang Mai 60 variety), which has medium Mg requirements, or sunflower (*Helianthus annuus*; Aguara 6 variety), which has high Mg requirements [21], were planted and thinned out to a single plant per pot 5 days after emergence. Tap water was used for daily watering. A basal dressing containing NPK fertilizer was applied a week after germination [22] to both soybean and sunflower. Hydroponic solutions A and B without Mg were used to ensure an optimum and constant supply of nutrients (Table 2). Ten-milliliter samples of stock solutions A and B were mixed and adjusted to 1 l to create a diluted nutrient solution. Then, 20 ml per pot of the diluted nutrient solution was used weekly from day 14 of emergence until harvesting.

Plant growth and nutrient accumulation measurement

Plant growth parameters were measured before harvesting (60 days). Plant height was measured from the soil surface to the highest growing tip, the number of leaves per plant was counted, and the stem diameter was measured from approximately 3 cm above the soil surface using a digital Vernier caliper. The number of pods in soybean and the head diameter in sunflower were recorded. Plant tissues for seed yield, leaf, stem, and roots were separated and weighed when fresh and after oven-drying at 70 °C to determine the dry weight. Each plant tissue was digested with H_2SO_4 for total N estimation and in a mixture (HNO_3–$HClO_4$; 3:1, v/v) for total Mg, P, K, and Ca estimation [5]. Nutrient uptake was calculated as the nutrient concentration in dry biomass compared to the weight of roots and shoots.

Magnesium use efficiency

Mg use efficiency (MgUE), Mg uptake efficiency (MgUpE), and Agronomic efficiency (AE) were calculated, respectively, using the following equations [18]: Mg use efficiency (MgUE) = Dry biomass yield/ Mg application rate (mg/mg); Mg uptake efficiency (MgUpE) = Crop Mg accumulation/Mg application rate (mg/mg); Agronomic efficiency (AE) = (Dry biomass fertilized crop − Dry biomass unfertilized crop)/Mg application rate (mg/mg).

Statistical analysis

The growth rates and nutrient uptake as means of four replicates with standard deviation were considered. Analysis of variance (ANOVA) was used to test whether treatment effects were significant, and means were separated using Duncan's multiple range test (DMRT) at a p value of $\leqslant 0.05$ [23] to assess the specific contrasts between pairs of means.

RESULTS

Plant growth

Mg fertilizer application promoted plant growth in both soybean and sunflower. The 50 and 100 mg Mg/kg application rates generated the highest plant growth relative to the growth without Mg fertilizer application (Table 3). There was no significant difference in the number of leaves, plant height, and root length for sunflower between the Mg applications.

Table 1 Physicochemical properties of Kho-hong (Kh) soil series.

pH	OM (g/kg)	Total N (g/kg)	Avail. P (mg/kg)	Extr. K (mg/kg)	Extr. Mg (mg/kg)	Extr. Ca (mg/kg)	Soil texture
4.73	27.82	0.91	4.16	12.55	12.20	65.38	Sandy loam

Table 2 Mixtures of nutrients in solutions A and B.

Fertilizer solution	Substance	Formula	Concentration (mg/l)
A	Calcium nitrate	$Ca\ (NO_3)_2$	1,797
	Iron(III)-EDTA(13% Fe^{3+})	$C_{10}H_{12}FeN_2O_8^-$	40
	Iron(II)-EDTA(6% Fe^{2+})	$C_{10}H_{12}FeN_2O_8^{-2}$	40
B	Potassium nitrate	KNO_3	1012
	Monopotassium phosphate	KH_2PO_4	105
	Monoammonium phosphate	$(NH_4)H_2PO_4$	190
	Manganese sulfate	$MnSO_4$	7.5
	Copper sulfate	$CuSO_4$	0.51
	Ammonium molybdate	$H_{24}Mo_7N_6O_{24}$	0.17
	Zinc sulfate	$ZnSO_4$	2.38
	Boric acid	$B(OH)_3$	6.23

Table 3 Effect of Mg fertilizer application on the growth of soybean and sunflower.

Mg application	Soybean				Sunflower			
(mg Mg/kg)	Height (cm)	Stem diameter (mm)	Leaf number (leaves)	Root length (cm)	Height (cm)	Stem diameter (mm)	Leaf number (leaves)	Root length (cm)
0	52.75 a	5.63 a	19.75 a	60.00 a	47.70	5.86 b	15.75	20.33
50	57.68 a	6.43 a	25.25 a	58.58 a	67.93	7.82 a	17.75	23.49
100	62.18 a	5.40 a	21.50 a	59.75 a	67.99	7.92 a	18.50	25.95
200	41.13 b	4.05 b	10.50 b	33.00 b	62.53	8.41 a	17.75	21.79
C.V. (%)	6.49	15.45	12.83	7.12	7.27	12.88	5.23	6.84
F-test	*	*	*	*	NS	*	NS	NS

NS = not significantly different ($p > 0.05$). * = significantly different ($p \leqslant 0.05$). Within a column, mean values ($n = 4$) labeled with different letters differed significantly by Duncan's multiple range test (DMRT) at a p-value of $\leqslant 0.05$. C.V. = coefficient of variation.

Table 4 Effect of Mg fertilizer application on soybean and sunflower biomass.

Treatment	Soybean dry weight (g)				
(mg/kg)	Stem	Leaf	Root	Seed	Whole plant
0	2.39 b	3.61 ab	2.08 a	4.84	12.92 b
50	3.39 a	4.22 a	1.76 a	6.48	16.10 a
100	3.08 a	3.76 ab	1.81 a	6.43	14.32 ab
200	2.10 b	2.43 b	1.34 b	5.77	8.66 bc
C.V. (%)	5.87	8.53	9.48	6.11	14.22
F-test	*	*	*	NS	*
Treatment	**Sunflower dry weight (g)**				
(mg/kg)	Stem	Leaf	Root	Seed	Whole plant
0	2.68	1.73 b	1.05	4.83 b	7.24 b
50	4.21	2.56 a	1.25	8.52 a	15.84 a
100	4.46	2.82 a	1.27	8.78 a	15.08 a
200	3.96	3.06 a	1.30	7.33 a	15.48 a
C.V. (%)	3.68	5.58	3.35	12.74	16.64
F-test	NS	*	NS	*	*

NS = not significantly different ($p > 0.05$). * = significantly different ($p \leqslant 0.05$). Within a column, mean values ($n = 4$) labeled with different letters differed significantly by DMRT at a p-value of $\leqslant 0.05$. C.V. = coefficient of variation.

Table 5 Effects of Mg application on nutrient accumulation and K:Mg accumulation ratio in soybean and sunflower.

Mg application (mg/kg)	Soybean				Sunflower			
	Nutrient accumulation (mg/plant)			K:Mg ratio in dry biomass	Nutrient accumulation (mg/plant)			K:Mg ratio in dry biomass
	N	P	K		N	P	K	
0	432 ab	32.06 b	152 ab	4.36:1	286 a	3.018 ab	175 a	6.49:1
50	521 a	44.57 a	184 a	2.98:1	267 ab	36.48 a	167 a	3.06:1
100	493 ab	35.65 ab	186 a	3.12:1	227 b	29.71 ab	156 a	2.84:1
200	392 b	29.22 c	119 b	2.57:1	142 c	22.91 c	101 b	2.35:1
C.V. (%)	25.36	18.30	12.27		23.55	11.59	18.24	
F-test	*	*	*		*	*	*	

* = Significantly different ($p \leqslant 0.05$). Within a column, mean values ($n = 4$) labeled with different letters differed significantly by DMRT at a p-value of $\leqslant 0.05$. C.V. = coefficient of variation.

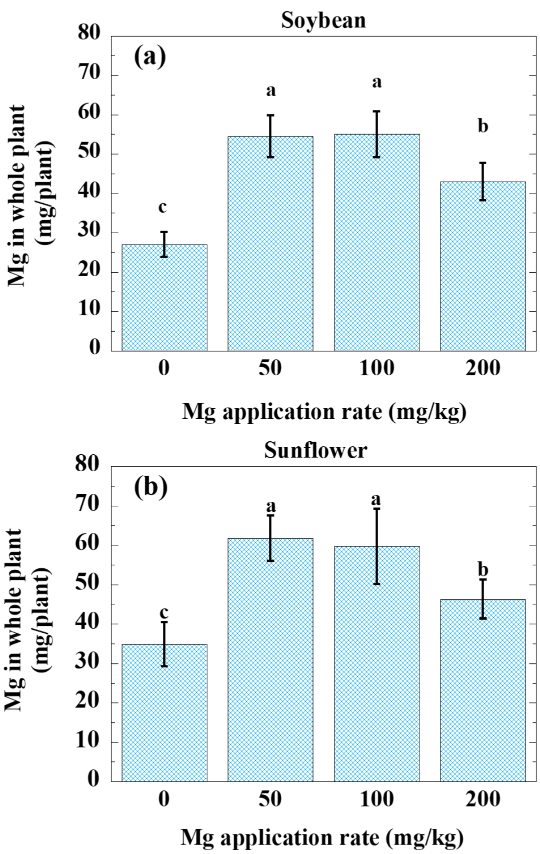

Fig. 1 Mg accumulation in soybean (a) and sunflower (b) dry biomass. Mean values labeled with different letters differed significantly at $p \leqslant 0.05$.

Biomass and nutrient accumulation

The application of Mg at the rates of 50 or 100 mg Mg/kg promoted biomass build-up (Table 4) and enhanced N, P, and K accumulation in soybean and sunflower (Table 5). In contrast, excessive Mg application (200 mg Mg/kg) suppressed the accumulation of N, P, and K in plants. The Mg application at 50 and 100 mg Mg/kg induced a K:Mg accumulation ratio of approximately 3:1 in soybean and sunflower dry biomass. Applying Mg significantly promoted Mg accumulation (Fig. 1), with the highest values obtained at 50 or 100 mg Mg/kg. However, the application of 200 mg Mg/kg conferred a slight decrease in plant growth and Mg accumulation in whole plants.

In sunflower, a lack of Mg created an imbalance in nutrient accumulation when Mg was not applied (Table 5), and also suppressed biomass accumulation (Table 4). The Mg application rates of 50 and 100 mg Mg/kg warranted better nutrient accumulation and significant biomass build-up (Table 4), with a resultant K:Mg uptake ratio of approximately 3:1 (Table 5).

Mg application at the rate of 50 mg Mg/kg resulted in an even Mg distribution within the seeds and leaves. In comparison, Mg application at the rate of 100–200 mg Mg/kg resulted in higher accumulation of Mg in the leaves and lower accumulation in the seeds in both soybean and sunflower (Fig. 2). In soybean leaves, the Mg concentration improved and was higher than the critical leaf Mg concentration at all application rates of Mg (Fig. 3a). In contrast, the leaf Mg concentration in sunflower crossed the critical limit at the 100 and 200 mg/kg Mg application rates (Fig. 3b).

Mg use efficiency in soybean and sunflower

MgUE, MgUpE, and AE were significantly higher after the application of Mg fertilizer at the rate at 50 mg Mg/kg (Table 6). A single gram of applied Mg fertilizer increased the dry biomass by 260 mg in both soybean and sunflower. Similarly, 1 mg of applied Mg fertilizer enhanced the MgUpE by 0.88 and 1.00 mg in soybean and sunflower, respectively. The AE was high, with the dry biomass yields increasing by 50 and 140 mg with the 50 mg/kg Mg application rate in soybean and sunflower, respectively.

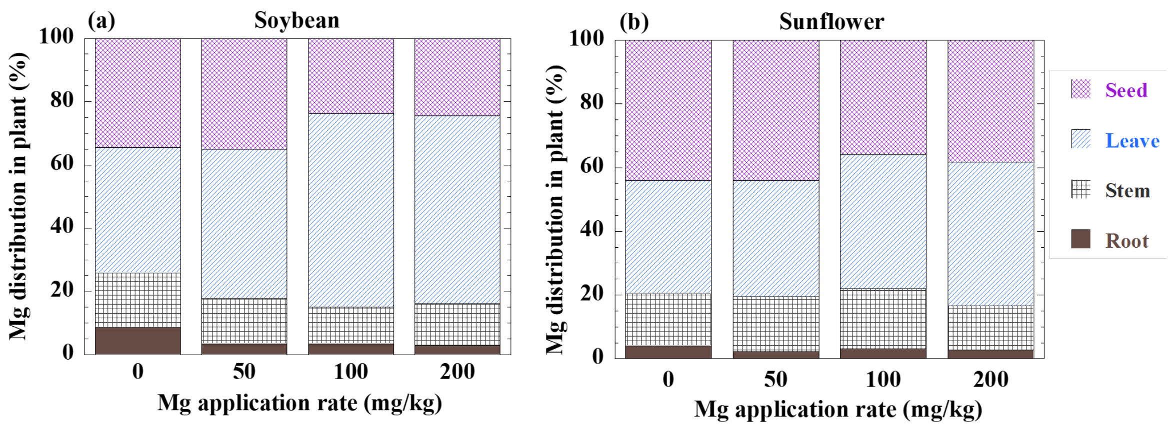

Fig. 2 Effect of Mg fertilizer application on Mg distribution in (a) soybean and (b) sunflower.

Table 6 Mg use efficiency in soybean and sunflower.

Mg application rate	Soybean			Sunflower		
(mg/kg)	Mg use efficiency (mg/mg)	Mg uptake efficiency (mg/mg)	Agronomic efficiency (mg/mg)	Mg use efficiency (mg/mg)	Mg uptake efficiency (mg/mg)	Agronomic efficiency (mg/mg)
50	260 a	0.88 a	50 a	260 a	1.00 a	140 a
100	130 ab	0.49 b	20 a	130 ab	0.53 b	70 a
200	40 b	0.20 c	–20 c	70 b	0.22 c	40 b
C.V. (%)	25.26	3.59	8.81	13.66	5.57	23.55
F-test	*	*	*	*	*	*

* = Significantly different ($p \leqslant 0.05$). Within a column, mean values ($n = 4$) labeled with different letters differed significantly by DMRT at ⩽ 0.05. C.V. = coefficient of variation.

DISCUSSION

Significant Mg fertilizer responses were observed in soybean and sunflower when the soil had limited extractable Mg. Plant biomass tended to be increased with Mg fertilizer application compared to without Mg fertilizer application; however, large doses affected plant growth negatively. Similarly, a yield increase was reported in previous studies after the plants received Mg [14, 24]. Mg plays a role in biochemical processes in plants; therefore, Mg deficiency in the soil (or its restricted accumulation) negatively affects metabolic processes in plants, resulting in various metabolic stresses that can retard plant growth and development [25]. In this study, we found that the Mg requirements for soybean and sunflower were different. The critical leaf Mg level in soybean was 3.0 g/kg, whereas it was 7.9 g/kg in sunflower [21]. As a result, the two crops have different Mg application and accumulation requirements to meet the critical Mg in plant concentration. Crops often respond in a similar manner to fertilizer application, but some responses are crop-specific [18, 26].

Increasing Mg fertilizer application enhanced leaf Mg content in both soybean and sunflower. However, the leaf Mg content in sunflower was below the critical Mg level when Mg fertilizer was applied to the soil at concentrations below 100 mg Mg/kg. Excessive Mg application (200 mg Mg/kg) suppressed plant productivity, which resulted in reduced Mg accumulation in the entire plant. Leaf Mg concentration tended to be increased based on the Mg application rate and showed leaf Mg concentrations that were higher than the optimal level. However, the plants did not show any Mg toxicity symptoms in this study. The majority of Mg in the plant was accumulated in the leaves. Plants store Mg in vacuoles, and this storage capacity protects the plant against harm from Mg oversupply [27, 28].

Mg fertilizer application enhanced Mg uptake in plants as well as the accumulation of other nutrients. Similarly, Mg application has been observed to promote N and P accumulation in rapeseed [25] and K and Ca uptake in cherry tomato (*Lycopersicon esculentum*) [29]. The application of Mg at a rate of 50 and 100 mg Mg/kg presented a K:Mg accumulation ratio of approximately 3:1, which has been demonstrated to be suitable for plant growth. A K:Mg accumulation ratio of 5–7:1 has been reported to be suitable for maize growth [14], while the leaf K:Mg ratio has been reported to be 3.87:1 in rubber trees grown in lowland

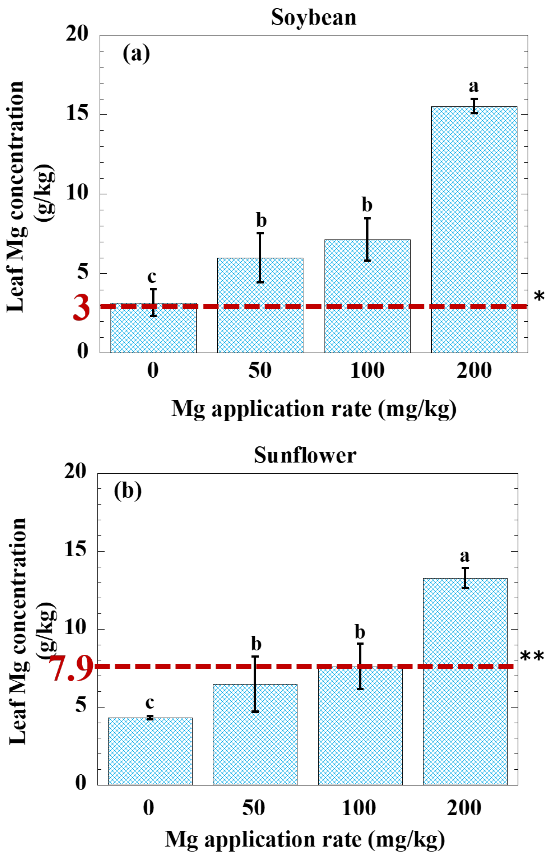

Fig. 3 Effect of Mg application on leaf Mg concentration in (a) soybean and (b) sunflower. *, ** = Critical leaf Mg level in soybean (3.0 g/kg) and sunflower (7.9 g/kg) [21], mean values labeled with different letters differed significantly at $p \leqslant 0.05$.

and 3.25:1 in rubber trees grown in upland [30]. The suitable K:Mg ratio in rice leaves was reported to be 22–25:1 [16], while that in sugarcane has been reported to be 5.38–6.13:1 [31]. The K:Mg accumulation ratio with excessive Mg application reduced plant growth, which may have been due to antagonism between the two elements when an imbalance was created. This phenomenon has been previously reported in cherry tomato [29] and pumelo [32]. Therefore, an unbalanced supply of Mg and K is not desirable because it affects plant growth, quality, and the distribution of nutrients across the plant [1].

The nutrient use efficiency is a versatile and complex index that is related to multiple biotic and abiotic factors. The efficiency was related to higher economic yield or unit increase in a trait of interest with a known quantity of applied or absorbed nutrients compared to other plants under similar growing conditions [18, 33]. Mg application showed significant effectiveness at the rates of 50 and 100 mg Mg/kg in MgUE, MgUpE, and AE in soybean and sunflower, with a high increase observed at Mg application at the rate of 50 mg Mg/kg (Table 6). The application of 50 and 100 mg Mg/kg enhanced plant growth and biomass accumulation relative to 0 or 200 mg Mg/kg applications, indicating the precise requirements of plants for Mg. A similar trend of plant condition improvements as a result of Mg application was observed in rapeseed and maize in previous studies [14, 25]. Another report showed that the majority of commercial crop cultivations in Thai soils contained low Extr. Mg [34]. Therefore, Mg fertilizer application is necessary to increase the soil Mg level in tropical soils with low Extr. Mg content. A dosage of 50–100 mg Mg/kg can be recommended to improve the growth, productivity, and efficiency of Mg fertilizer application to soybean and sunflower.

CONCLUSION

Application of Mg fertilizer to soil with low Mg content promotes growth and nutrient accumulation in plants. However, high applications suppress biomass and nutrient accumulation; therefore, Mg should be applied precisely. A K:Mg ratio of approximately 3:1 was observed to be suitable for soybean and sunflower growth. This study suggests that Mg fertilizer application at the rate of 50–100 mg Mg/kg can be recommended for high productivity and Mg fertilizer efficiency for soybean and sunflower grown in tropical Ultisols soils with low extractable Mg. However, the application rate for other commercial crops must be verified in future studies.

Acknowledgements: This research was financially supported by the Prince of Songkla University, Graduate School, Hat Yai, Songkhla, Thailand.

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