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Effect of Magnesium on Mineral Nutrition, Chlorophyll, Proline and Carbohydrate Concentrations of Sweet Orange (*Citrus sinensis* cv. Newhall) Plants

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Abstract: Magnesium is an essential nutrient for the growth and development of plants. Its deficiency is becoming a growing concern in many citrus orchards worldwide, adversely affecting numerous functions in plants and limiting their productivity and quality. Three-year-old orange (*Citrus sinensis* cv. Newhall) plants grafted on Swingle citrumelo (*C. paradisi* Macf. × *Poncirus trifoliata* L.) rootstock were irrigated for 63 days with nutrient solutions containing 0, 12, 24, 48, 96, and 192 mg Mg L⁻¹. Thereafter, Mg deficiency-induced changes were investigated in leaf chlorophyll concentration and fluorescence, and in proline and carbohydrate concentration in leaves and roots, as well as in the nutritional status of leaves, stems, and roots. Magnesium concentration in the nutrient solution was positively correlated with the concentration of Mg (leaves, stems, roots), Ca (rootstock's stem), K (roots), and Fe (leaves, rootstock's stem), as well as with the total Mg absorption. However, Mg concentration in the nutrient solution was negatively correlated with the concentration of Mn (rootstock's stem, roots), Ca (leaves, scion's stems, roots), and Fe (roots), as well as with the total absorption of Mn, Fe, P, K, and Ca. The lower values of the chlorophyll fluorescence parameters were observed by the effect of the highest concentration of Mg. As far as leaf chlorophyll concentration and carbohydrate and proline content of leaves and roots, they were not affected by the Mg treatments. Concluding, this research highlights the significance of Mg management in citrus farming, offering insights into increasing Mg concentrations, understanding root mechanisms in Mg absorption, and suggesting the benefits of fertilization to address Mg deficiency. It emphasizes the importance of careful Mg fertilizer dosages, considering other nutrient interactions, and provides valuable guidance for optimizing Mg nutrition and overall nutrient management in sweet orange trees.

Keywords: chlorophyll fluorescence; deficiency; macronutrient; photosynthesis; plant nutrition; rootstock; stress



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1. Introduction

Magnesium is one of the essential nutrient elements for normal plant growth and development and numerous key functions in plants [1]. It is characterized as a macronutrient, since it is required in relatively high concentrations (0.15–0.35% Mg dry weight; d.w.) in order to achieve maximum growth of different plant organs [2]. Magnesium is a structural element of the chlorophyll molecule; it activates more than 300 enzymes and contributes to the stabilization of certain subcellular structures (organelles), such as ribosomes [3,4]. Moreover, it is found to play an important role in plant photosynthesis, carbohydrate transport,

nucleic acid and protein synthesis, and also in the generation of reactive oxygen species (ROS) [5–9]. Since Mg is extremely mobile within the plant and its remobilization occurs from older leaves to younger ones, acute Mg deficiency causes interveinal chlorosis of older and fully developed leaves, due to the crucial functions of Mg in chlorophyll and protein production [2,10]. Mg deficiency is especially noted in seeded *Citrus* cultivars, because of the translocation of Mg to the seeds [11]. Some specific symptoms of Mg deficiency in *Citrus* species are yellow blotches along the midrib on mature leaves, which spreads until the pattern covers most of the leaf, apart from a characteristic delta-shaped dark green area at the base [11].

Several studies have noted the connection between Mg nutrition and plant growth in a variety of higher plants during the past few decades [5,12–16]. Worldwide, Mg deficiency is frequently observed in many agricultural crops, including citrus. Interestingly, according to an investigation, up to 83% of the soils from 152 citrus orchards in a province of China were rated as low in Mg [17]. Mg nutrition affects crop productivity and quality [4,15,16]; therefore, Mg increased the quality in oranges and improved the flavor, soluble solids, sugar, and vitamin C content in grapefruit, in comparison with fruit from Mg-deficient trees [18]. Mg deficiency affects the uptake of nutrients and their concentrations in stems, leaves, and roots [19,20]. Under Mg deficiency conditions, there is a reduction in photosynthesis and protein synthesis, resulting in disorder of the normal function and structure of plant cells, tissues, and organs [2,17,21,22]. Numerous higher plants, including *Citrus*, have been reported to present decreased leaf CO₂ absorption in response to Mg shortage [17,22]. Considering the antagonistic effects of an unbalanced supply of cationic nutrients (K, NH₄, Ca, Mg), these deficiencies in the plant's physiology may also simply be connected to nutritional imbalances, such as K, Ca, and Mn imbalances, in plants [1].

Some of the most significant evergreen fruit trees are those belonging to the *Citrus* genus. Magnesium shortage is a common physiological condition that affects citrus plants and results in a decrease in the rate of photosynthetic activity, yellowing, and senescence of the leaves [17,23], all of which have a negative impact on crop yield and quality [7,20,24–30]. Due to soil acidification [31] and producers' overuse of N, P, and K chemical fertilizers [27,32], Mg shortage is now a common occurrence in orchards. Other competing cations, including Ca²⁺, H⁺, NH₄⁺, and Al³⁺, also had a similar antagonistic effect [7].

There is insufficient information on the differential responses of various *Citrus* genotypes when exposed to Mg deficiency, and very few reports on citrus scion-rootstock combinations under Mg-poor conditions [33]. On the other hand, extra Mg supply enhances citrus trees' biochemical and physiological responses to alleviate the harmful effects of unfavorable environmental conditions, such as excessive heat and irradiation [34]. Similarly, Mg adequacy in trees increases their cold resistance; thus, frost caused severe defoliation and total fruit loss in Mg-deficient trees, whereas neighboring trees treated with Mg lost only a few leaves [18]. The purpose of the current study was to investigate how Mg fertilization affected the grafted sweet orange plants' development, nutritional status, and concentrations of carbohydrates, proline, and chlorophyll.

2. Materials and Methods

2.1. Plant Material and Experimental Design

In the current study, 36 (6 per treatment) three-year-old sweet orange (*Citrus sinensis* cv. Newhall) plants budded on Swingle citrumelo (*C. paradisi* Macf. × *Poncirus trifoliata* L.) rootstock were used. Their height, stem diameter, and leaf area were all the same. The plants were cultivated separately in black plastic bags (3 L) filled with an inert sand:perlite combination (1:1, v/v). The experiment was carried out in the experimental greenhouse of the Laboratory of Pomology, situated on the farm of the Aristotle University of Thessaloniki (40.53° N, 22.99° E), from April to June. Climatic parameters were monitored by a weather station located inside the glasshouse. The minimum, maximum, and averaged air temperatures were 15.2, 33.8, and 24.9 °C, respectively.

After transplantation, the plants were irrigated every 3 days, according to their needs, with good-quality tap water for 35 days, and, after that period, they were irrigated every 2 days with a half-strength Hoagland's nutrient solution [35]. The macronutrients of the nutrient solution, except for Mg, were supplied at half-strength, while the micronutrients, except for Mn (1.1 mg L^{-1}), were supplied at double-strength. As far as Mg is concerned, six concentrations were tested, i.e., 0, 12, 24, 48, 96, and 192 mg Mg L^{-1} . The standard concentration of Mg in Hoagland's No. 2 nutrient solution is 24 mg L^{-1} [35]. The amount of the nutrient solution used for each watering was sufficient to fill the planting medium's pores and permit some leaching from the bottom of it. Furthermore, with this procedure, the Mg concentrations in the planting media were identical to the original solution [36].

2.2. Measurements and Analysis

After 63 days, the experiment was completed and the plants were harvested, split into scion's leaves and stems and rootstock's stem and roots, respectively. All the collected samples were weighed (fresh weight; f.w.), rinsed once with tap water and twice with deionized water, then dried in an oven at 75°C to a consistent dry weight, before being crushed into a fine powder that could pass through a 30-mesh screen. Afterwards, for the nutrients' analyses, 0.5 g of the dried sample was dry ashed for 6 h at 550°C , then dissolved in 3 mL of 6 N HCl, and, finally, diluted with deionized water. The concentrations of P, K, Ca, Mg, Fe, Mn, and Zn were determined using atomic absorption spectroscopy (Perkin-Elmer model 2380; Perkin-Elmer, Salem, MA, USA). Moreover, the concentration of P was determined colorimetrically (470 nm) by using the ammonium phosphovanadomolybdate yellow method [37]. Macronutrient concentrations were expressed in % d.w., while those of micronutrients, i.e., Fe, Mn, and Zn, were expressed in mg kg^{-1} d.w. The content (absolute quantity) of each nutrient existing in each plant part, and the total in the entire plant, was calculated by multiplying the concentration of each nutrient found in the leaves, scion's stems, rootstock's stem, and root by the respective dry weight of each plant part. The nutrient use efficiency (NUE), which is defined as the amount of plant biomass produced per unit of a mineral nutrient, was also assessed for each nutrient [36].

Chlorophyll fluorescence parameters (F_v/F_m , F_v/F_0 ; F_0 : initial fluorescence, F_m : maximum fluorescence, $F_v = F_m - F_0$: variable fluorescence) were measured on the 62nd day with a Plant Efficiency Analyzer (Hansatech 2.02), in order to determine possible impairments to photosystem II (PSII). For this reason, one fully-grown leaf per plant, located at the 3rd or 4th node from the top to the base of a stem, was measured after pre-conditioning in the dark for 20 min. In the following, each of these leaves was detached and used for the determination of the concentrations of chlorophyll, total soluble carbohydrates, and free proline.

For the determination of chlorophyll concentration, 7 leaf discs, 10 mm in diameter, were sampled from each leaf. The remaining leaf tissue was put in the fridge (-20°C) until the determination of proline and carbohydrates. Leaf chlorophyll was extracted with ethanol (96%) in a water bath (78°C). Total chlorophyll concentration (Chl_{a+b}) was calculated from the equations given by Wintermans and De Mots [38]. Furthermore, 0.1 g of each leaf was cut into small pieces, placed in a glass vial containing 10 mL of 80% (v/v) ethanol, and heated at 60°C for 30 min. The extract was then filtered and diluted with 80% (v/v) ethanol up to 20 mL [38]. Free proline and total soluble carbohydrates were both assayed in the aforementioned extract, following the acid ninhydrin reagent and the anthrone methods, respectively [39]. The same procedure was followed for the determination of carbohydrates and proline in root samples that were collected during the harvest of plants at the end of the experiment.

2.3. Statistical Analysis

Experiments were set up following a completely randomized experimental design. The data were subjected to analysis of variance (ANOVA) using the SPSS-17 for Windows statistical package (SPSS INC., Chicago, IL, USA). For comparison of the means, the Duncan

multiple range test ($p \leq 0.05$) was employed. The correlation coefficients between the Mg concentration in the nutrient solution and the values of various determined parameters were also computed using the bivariate correlation analysis tool of the above-mentioned statistical package and selecting the Pearson's correlation test.

3. Results and Discussion

Magnesium is involved in many physiological and biochemical processes in plants, contributing mainly to photosynthesis and the transport of photo-assimilates [40,41]. Mg deficiency can have a negative effect on plant biomass production, since the transport of sucrose from source leaves to sink organs is inhibited [42,43]. On the contrary, the total fresh and dry weight of the sweet orange plants of the present study was not significantly affected by the concentration of Mg in the nutrient solution (Table 1). However, the plants irrigated with the solution containing 48 mg Mg L⁻¹ achieved the highest values of the total fresh and dry plant weight, while those treated with the highest Mg concentration presented the lowest ones (Table 1).

Table 1. Effect of Mg concentration of the nutrient solution (0–192 mg L⁻¹) on total sweet orange plant weight and on Mg, Ca, K, P, Fe, Mn, and Zn concentrations of different plant parts (leaves, scion's stems, rootstock's stem, root).

Parameter		Mg Concentration of the Nutrient Solution (mg L ⁻¹)					
		0	12	24	48	96	192
Mg (% d.w. *)	Leaves	0.26 ± 0.03 d ¹	0.30 ± 0.05 cd	0.33 ± 0.03 bc	0.36 ± 0.02 b	0.37 ± 0.04 ab	0.40 ± 0.03 a
	Scion's stems	0.19 ± 0.02 d	0.21 ± 0.02 bc	0.21 ± 0.01 bc	0.23 ± 0.02 b	0.22 ± 0.02 bc	0.33 ± 0.06 a
	Rootstock's stem	0.09 ± 0.01 b	0.09 ± 0.01 b	0.09 ± 0.01 b	0.10 ± 0.01 ab	0.10 ± 0.01 ab	0.11 ± 0.01 a
	Roots	0.28 ± 0.03 bc	0.27 ± 0.03 c	0.30 ± 0.02 bc	0.30 ± 0.02 bc	0.31 ± 0.03 ab	0.34 ± 0.04 a
Ca (% d.w.)	Leaves	2.67 ± 0.14 a	2.77 ± 0.13 a	2.66 ± 0.09 a	2.44 ± 0.14 b	2.46 ± 0.15 b	2.19 ± 0.08 c
	Scion's stems	1.52 ± 0.19 ab	1.65 ± 0.19 a	1.62 ± 0.25 a	1.37 ± 0.09 bc	1.50 ± 0.13 ab	1.27 ± 0.17 c
	Rootstock's stem	0.89 ± 0.07 b	0.93 ± 0.04 b	0.93 ± 0.08 b	0.97 ± 0.12 b	0.96 ± 0.06 b	1.06 ± 0.04 a
	Roots	1.25 ± 0.09 a	1.25 ± 0.16 a	1.22 ± 0.09 a	1.25 ± 0.09 a	1.23 ± 0.09 a	1.00 ± 0.09 b
K (% d.w.)	Leaves	2.22 ± 0.19 a	2.25 ± 0.12 a	2.21 ± 0.10 a	2.25 ± 0.18 a	2.31 ± 0.10 a	2.30 ± 0.08 a
	Scion's stems	1.58 ± 0.14 a	1.55 ± 0.18 a	1.50 ± 0.12 a	1.57 ± 0.13 a	1.48 ± 0.36 a	1.65 ± 0.25 a
	Rootstock's stem	0.47 ± 0.05 a	0.39 ± 0.06 a	0.44 ± 0.04 a	0.44 ± 0.04 a	0.43 ± 0.10 a	0.46 ± 0.06 a
	Roots	1.31 ± 0.07 b	1.27 ± 0.24 b	1.27 ± 0.12 b	1.47 ± 0.14 ab	1.47 ± 0.19 ab	1.60 ± 0.15 a
P (% d.w.)	Leaves	0.24 ± 0.03 a	0.24 ± 0.02 a	0.23 ± 0.02 a	0.23 ± 0.02 a	0.24 ± 0.05 a	0.24 ± 0.04 a
	Scion's stems	0.26 ± 0.02 a	0.27 ± 0.02 a	0.23 ± 0.03 a	0.25 ± 0.02 a	0.20 ± 0.10 a	0.25 ± 0.10 a
	Rootstock's stem	0.07 ± 0.01 a	0.07 ± 0.01 a	0.06 ± 0.01 a	0.07 ± 0.01 a	0.06 ± 0.01 a	0.06 ± 0.01 a
	Roots	0.09 ± 0.01 a	0.10 ± 0.01 a	0.11 ± 0.02 a	0.10 ± 0.01 a	0.09 ± 0.01 a	0.11 ± 0.02 a
Fe (mg kg ⁻¹ d.w.)	Leaves	61.05 ± 5.48 bc	62.00 ± 2.26 bc	59.17 ± 2.73 c	62.83 ± 3.86 bc	65.50 ± 5.53 ab	69.92 ± 6.46 a
	Scion's stems	45.42 ± 1.02 a	44.42 ± 3.83 a	42.27 ± 10.72 a	42.03 ± 4.57 a	34.54 ± 17.02 a	43.00 ± 2.61 a
	Rootstock's stem	32.17 ± 2.36 a	35.55 ± 5.86 a	34.83 ± 4.17 a	35.33 ± 3.27 a	36.75 ± 3.36 a	39.58 ± 3.48 a
	Roots	1040 ± 71 ab	1158 ± 237 a	980 ± 114 abc	1005 ± 152 ab	947 ± 126 bc	804 ± 137 c
Mn (mg kg ⁻¹ d.w.)	Leaves	14.33 ± 1.25 a	9.25 ± 1.29 bc	9.00 ± 1.10 c	10.92 ± 1.16 b	9.67 ± 2.09 bc	9.67 ± 0.88 bc
	Scion's stems	3.92 ± 0.92 a	4.08 ± 0.97 a	3.58 ± 0.49 a	3.89 ± 0.71 a	3.32 ± 1.82 a	4.33 ± 0.75 a
	Rootstock's stem	4.00 ± 0.45 a	3.25 ± 0.52 a	2.75 ± 0.76 b	3.17 ± 0.41 bc	3.00 ± 0.63 bc	2.33 ± 0.41 c
	Roots	43.67 ± 8.48 a	45.17 ± 7.00 b	35.00 ± 6.81 abc	33.50 ± 4.04 b	34.50 ± 3.67 bc	27.17 ± 4.12 c
Zn (mg kg ⁻¹ d.w.)	Leaves	9.08 ± 0.58 a	9.50 ± 0.95 a	9.83 ± 0.68 a	10.67 ± 1.47 a	9.25 ± 0.61 a	9.50 ± 1.14 a
	Scion's stems	8.86 ± 1.82 a	10.12 ± 2.21 a	9.08 ± 2.76 a	10.78 ± 2.03 a	9.12 ± 4.66 a	9.08 ± 2.22 a
	Rootstock's stem	4.25 ± 0.27 c	5.08 ± 0.86 abc	5.83 ± 1.17 a	5.58 ± 0.66 a	5.33 ± 0.61 ab	4.58 ± 0.49 bc
	Roots	11.00 ± 0.89 b	13.67 ± 1.97 a	14.67 ± 1.37 a	16.33 ± 3.56 a	15.33 ± 1.21 a	14.33 ± 2.94 a
Total plant weight	Fresh weight (g)	91.84 ± 8.53 a	91.52 ± 16.76 a	87.01 ± 10.72 a	93.81 ± 10.26 a	84.29 ± 12.16 a	83.00 ± 14.01 a
	Dry weight (g)	34.46 ± 3.19 a	35.12 ± 7.29 a	32.73 ± 3.18 a	35.80 ± 4.71 a	32.72 ± 4.59 a	30.86 ± 5.81 a

¹ Means (±S.D.) in the same row followed by different letters are significantly different (Duncan's test $p < 0.05$); $n = 6$. * d.w.: dry weight.

Mg deficiency affects the uptake of nutrients and their concentrations in stems, leaves, and roots [20]. According to the results, the concentration of Mg in the nutrient solution was significantly and positively correlated [$r = (+0.464, p < 0.01) - (+0.802, p < 0.001)$], with the concentration of Mg (leaves, scion's and rootstock's stems, roots), Ca (rootstock's stem), K (roots), and Fe (leaves, rootstock's stem), the total absorption of Mg, and the ability of plants to use Mn and Fe more efficiently (Table 2). However, the concentration of Mg in the nutrient solution was correlated significantly and negatively [$r = (-0.371, p < 0.05) - (-0.808, p < 0.001)$], with the concentration of Mn (rootstock's stem, roots), Ca (leaves, scion's stems, roots), and Fe (roots), the total absorption of Mn, Fe, P, K, and

Ca, and the ability of plants to use Mg more efficiently (Table 2). According to Fageria (1974) [44], increasing the availability of Mg also negatively affected the absorption of Ca and K uptake by peanut plants, whereas P absorption was not affected. Given the existence of significant negative interactions between the availability of Mg in the rhizosphere and the total absorption of some other nutrients (K, P, Ca, Mn, Fe), as well as their concentrations in the leaves (Ca), great attention is required regarding the applied doses of Mg fertilizers.

Table 2. Correlation coefficient (*r*) between Mg concentration of the nutrient solution and P, K, Ca, Mg, Mn, Zn, and Fe concentrations of various plant parts, total element absorption, and element use efficiency of sweet orange plants.

Parameters		P	Macronutrients			Micronutrients		
			K	Ca	Mg	Mn	Zn	Fe
Nutrient concentrations of various plant parts	Leaves	0.095	0.248	−0.808 ***	0.722 ***	−0.299	−0.029	0.605 ***
	Scion's stems	−0.138	0.124	−0.497 **	0.802 ***	0.098	−0.058	−0.137
	Rootstock's stem	−0.280	0.142	0.588 ***	0.579 ***	−0.547 **	−0.118	0.487 **
	Roots	0.213	0.584 ***	−0.612 ***	0.634 ***	−0.633 ***	−0.226	−0.544 **
Total element absorption		−0.599 ***	−0.371 *	−0.495 **	0.511 **	−0.700 ***	−0.175	−0.717 ***
Element use efficiency		0.239	−0.029	0.177	−0.677 ***	0.478 **	−0.151	0.464 **

n = 36; *** *p* < 0.001; ** *p* < 0.01; * *p* < 0.05.

Higher concentrations of Mg were recorded in the leaves of the plants, followed by the roots, the stems of the scion, and the stem of the rootstock (Table 1). In addition, concentrations of Mg in all plant parts were significantly higher when the plants were irrigated with the nutrient solution containing 192 mg Mg L^{−1}, compared to 0–48 mg Mg L^{−1} (Table 1). The total amount of Mg per plant, and its total nutrient absorption, was found to be significantly increased when the nutrient solution contained 192 mg Mg L^{−1}, compared to 0–24 mg Mg L^{−1} (Table 3). As far as the Mg use efficiency by the sweet orange plants, it decreased significantly and gradually as its concentration in the nutrient solution increased (Table 3).

Table 3. Effect of Mg concentration of the nutrient solution (0–192 mg L^{−1}) on Mg, Ca, K, P, Fe, Mn, and Zn total amount per sweet orange plant and use efficiency.

Parameter		Mg Concentration of the Nutrient Solution (mg L ^{−1})					
		0	12	24	48	96	192
Mg	Total amount per plant (mg)	51.11 ± 4.78 c ¹	57.95 ± 8.79 bc	56.74 ± 5.05 bc	62.90 ± 4.13 ab	60.36 ± 3.62 abc	67.84 ± 14.21 a
	Use efficiency (mg d.w./mg Mg)	678.76 ± 85.06 a	603.15 ± 58.88 ab	577.54 ± 38.50 b	570.14 ± 71.95 b	543.60 ± 79.17 b	459.11 ± 56.08 c
Ca	Total amount per plant (mg)	452.23 ± 29.74 a	424.06 ± 66.37 a	413.49 ± 40.40 a	415.99 ± 40.79 a	402.01 ± 52.79 a	365.95 ± 30.06 a
	Use efficiency (mg d.w./mg Ca)	76.21 ± 5.01 a	82.71 ± 11.31 a	79.15 ± 1.35 a	86.55 ± 12.23 a	81.56 ± 6.09 a	84.11 ± 12.42 a
K	Total amount per plant (mg)	331.83 ± 15.79 a	318.01 ± 35.32 ab	298.51 ± 18.83 b	337.67 ± 29.20 a	311.50 ± 19.79 ab	290.84 ± 25.46 b
	Use efficiency (mg d.w./mg K)	103.76 ± 6.65 a	109.56 ± 12.57 a	109.84 ± 10.70 a	106.05 ± 9.92 a	105.77 ± 19.14 a	106.35 ± 19.87 a
P	Total amount per plant (mg)	38.38 ± 3.39 a	36.53 ± 5.04 ab	35.08 ± 3.46 ab	36.84 ± 2.12 ab	33.17 ± 3.34 bc	30.61 ± 1.71 c
	Use efficiency (mg d.w./mg P)	902.10 ± 93.76 a	955.95 ± 107.57 a	937.03 ± 90.52 a	975.18 ± 146.43 a	990.64 ± 138.35 a	1009.85 ± 194.9 a
Mn	Total amount per plant (μg)	4290 ± 290 a	3878 ± 350 b	3129 ± 443 cd	3298 ± 238 c	2846 ± 372 de	2705 ± 273 e
	Use efficiency (mg d.w./μg Mn)	8.08 ± 1.09 c	9.01 ± 1.41 bc	10.63 ± 1.73 ab	10.91 ± 1.71 ab	11.58 ± 1.54 a	11.51 ± 2.37 a
Zn	Total amount per plant (μg)	2199 ± 91 ab	2344 ± 228 abc	2404 ± 80 bc	2735 ± 227 d	2485 ± 58 c	2168 ± 227 a
	Use efficiency (mg d.w./μg Zn)	15.65 ± 0.92 a	14.95 ± 2.70 a	13.66 ± 1.76 a	13.22 ± 2.48 a	13.15 ± 1.58 a	14.25 ± 2.15 a
Fe	Total amount per plant (μg)	71,591 ± 4295 cd	72,105 ± 7047 d	62,928 ± 11,334 bc	63,332 ± 2952 bc	56,337 ± 4348 ab	50,543 ± 8353 a
	Use efficiency (mg d.w./μg Fe)	0.48 ± 0.05 a	0.50 ± 0.13 a	0.53 ± 0.09 a	0.56 ± 0.05 a	0.58 ± 0.06 a	0.62 ± 0.13 a

¹ Means (±S.D.) in the same row followed by different letters are significantly different (Duncan's test *p* < 0.05); *n* = 6.

Despite the wide range of Mg concentrations (0–192 mg L⁻¹) administered to the plants through the nutrient solution, a great difficulty was observed in increasing the concentrations of Mg in the various plant organs, as well as the total amount of Mg absorbed by the plants. These data not only adequately explain the sensitivity of sweet orange plants to Mg deficiency, but also indicate the existence of a root mechanism that strictly controls the absorption of Mg. On the other hand, the fact that the change in the concentration of Mg in the nutrient solution had a more positive effect on the concentrations of Mg in the scion's tissues (mainly in the leaves) than in the rootstock's ones mitigates the difficulty of correcting the shortage of Mg in sweet orange trees by applying fertilizers to the soil.

Lack of magnesium impacts nutrient uptake and concentrations in stems, leaves, and roots [19,22]. According to other findings [23,27,45], Mg deficiency may increase the concentrations of other cations, such as Ca, K, and Mn. Our results also support the competitive effect of Mg on Ca uptake. More specifically, the tissues of the scion (leaves, stems) and the roots concentrated considerably less Ca at the presence of 192 mg Mg L⁻¹, compared to the other Mg treatments (Table 1). Conversely, the Ca concentrations of the rootstock's stem were found to be significantly higher in the presence of 192 mg Mg L⁻¹ (Table 1). However, the Ca use efficiency of the sweet orange plants was not significantly affected by Mg nutrition (Table 2).

The total amount of K per plant, and its total absorption from the nutrient solution, was significantly reduced in the treatment of 192 mg Mg L⁻¹, compared to the treatment where the plants were developed in the absence of Mg (Table 1). Plant K concentrations decreased with the supply of Mg in maize and coffee [46,47]. The antagonistic effect of Mg on K has been reported in *Citrus* [23,27,45]. However, the K use efficiency and K concentrations in the leaves, the stems of the scions, and the rootstock were not significantly influenced by the concentration of Mg in the nutrient solution (Tables 1 and 3). The roots of the plants treated with the nutrient solutions 48–192 mg Mg L⁻¹, particularly in the treatment 192 mg Mg L⁻¹, contained significantly more K than those of the plants under the treatments 0–24 mg Mg L⁻¹ (Table 1). Depending on the ratio of K to Mg in the growth medium, and the plant species employed in the studies, the literature claims that Mg has either a moderate synergistic, an antagonistic, or even no influence on K absorption [48]. The results showed that there was no significant effect of Mg on either P concentrations of various plant parts or the P use efficiency (Tables 1 and 3). In contrast, it was found that increasing the concentration of Mg in the nutrient solution caused a gradual decrease in the total amount of P per plant (Table 3). This decrease was particularly significant in the presence of higher concentrations of Mg in the nutrient solution (96–192 mg Mg L⁻¹).

Significant decrease in Mn concentrations of the roots was measured when the plants were grown at Mg concentrations higher than 24 mg Mg L⁻¹ (Table 1). Also, the presence of Mg in the nutrient solution, irrespective of its concentration (12–192 mg Mg L⁻¹), resulted in a significant reduction of Mn concentrations in the leaves and the stem of the rootstock, as well as of the total amount of Mn being absorbed by the plants (Tables 1 and 3). Moreover, the Mn use efficiency of plants grown under the influence of the higher Mg concentrations in the nutrient solution (96–192 mg Mg L⁻¹) was significantly increased compared to the other Mg treatments (0–48 mg Mg L⁻¹) (Table 3). This contradicts research on *Citrus* [23] and other species [19,46], which found that Mg deficit increased the content of Mn in the roots and leaves. The competitive effects of Mg on Mn, however, may differ, depending on the genotype of plant and the nutrient concentrations in the medium [46].

Magnesium concentration of the nutrient solution did not significantly affect the concentration of Zn in the scion or the Zn use efficiency of the sweet orange plants (Tables 1 and 3), indicating that there was not an antagonistic interaction between the two nutrients. However, the total absorption of the Zn per plant, as well as its concentrations in the stem of the rootstock, initially increased with the increase of Mg in the nutrient solution, and then decreased (Tables 1 and 3). Additionally, root Zn concentration was significantly increased in all Mg treatments (12–192 mg Mg L⁻¹) (Table 1). This is in

contrast to previous studies performed, not only in *Citrus*, where the Mg concentration of the nutrient solution was negatively correlated with leaf and root Zn concentration [19,46].

There was no significant effect of Mg on Fe concentrations of the stems of the scion and the rootstock, nor on the Fe use efficiency of plants (Tables 1 and 3). In contrast, it was found that increasing the concentration of Mg in the nutrient solution caused a gradual decrease in the total amount of Fe per plant and, therefore, the ability of the plants to absorb Fe from the nutrient solution (Table 3). Indeed, this decrease was particularly significant in plants grown in the presence of high concentrations of Mg in the nutrient solution (96–192 mg Mg L⁻¹). It is worth pointing out that, while, in these treatments, markedly elevated concentrations of Fe were observed in plant leaves, the corresponding values in the roots were significantly reduced. Similarly, Mg deficiency decreased the concentration of Fe by 45.46% in the roots of sweet orange seedlings [20]. In general, there is an inconsistency in the Mg effect on Fe that is also supported by Ye et al. (2019) [23], experimenting with sweet orange, who suggested that Mg-deficiency either decreased or did not alter Fe concentration in the leaf blades, but it increased its concentration in leaf veins while Fe concentration was decreased in veins of lower leaves.

Magnesium deficiency usually leads to the reduction of leaf chlorophyll concentrations, destruction of photosystems, and deceleration of photosynthetic electron transport [23,49–51]. The values of the F_v/F_m ratio, an indicator of photoinhibitory effects on the photosystem II of photosynthesis, varied between 0.76 and 0.82, depending on the concentration of Mg in the nutrient solution (Figure 1a). The corresponding values of the F_v/F_0 ratio were between 3.43 and 4.49 (Figure 1a). This is in contrast to the findings of Ye et al. (2019) [23], where Mg-deficient orange seedlings presented decreased F_v/F_0 in leaves, indicating that Mg deficiency might impair the structure of thylakoids and inhibit the photosynthetic electron transport. Although the concentration of Mg in the plant irrigation solution did not statistically affect the values of the parameters mentioned above (F_v/F_m , F_v/F_0), their lower values were observed under the influence of the highest concentrations of Mg. In a previous study with orange seedlings [23], Mg deficiency decreased F_v/F_m in leaves, which, together with other fluorescence parameters, demonstrated that photoinhibition occurred in Mg-deficient leaves [23,52,53].

Although Mg, as the central atom, is an essential constituent of chlorophyll, the total chlorophyll concentration (a + b) was not significantly affected by the concentration of Mg in the nutrient solution (Figure 1b). Similarly, Ye et al. (2019) [23] reported that Mg deficiency had no influence on the concentration of Chl_{a+b} in the upper leaves of orange seedlings, while it lowered it in the middle and lower leaves. Moreover, under Mg sufficiency, the concentration did not vary with leaf positions. Depending on the concentration of Mg in the nutrient solution, and the way of expressing the results, the concentration of chlorophyll in the sweet orange leaves of “Newhall” ranged between 9.05–9.98 mg g⁻¹ d.w., whereas, when expressed per unit area, its values ranged between 41.29 µg cm⁻² and 47.23 µg cm⁻² (Figure 1b). It is not the Mg bound to chlorophyll that is restricting its synthesis under Mg-deficient conditions, as evidenced by the fact that the proportion of total Mg bound to chlorophyll varies on Mg status and that its highest values are measured in Mg-deficient plants [2].

The concentration of carbohydrates in the sweet orange leaves ranged from 57.54 to 69.41 µmol g⁻¹ d.w., depending on the concentration of Mg in the nutrient solution (Figure 1c). Their concentration in the plant roots was two- to three-times smaller (24.78–29.96 µmol g⁻¹ d.w.) than those of the leaves (Figure 1c). The concentration of Mg in the nutrient irrigation did not significantly affect the concentration of carbohydrates in the leaves and the roots of the plants (Figure 1c). Nevertheless, the lower values were measured in the leaves of the plants irrigated with the highest amount of Mg, while, in the same treatment, the roots of the plants contained the highest level of carbohydrates (Figure 1c). Under Mg deficiency conditions, the accumulation of non-structural carbohydrates (free-soluble) in plant leaves is usually observed [2]. However, a similar decrease in soluble carbohydrates in “Newhall” orange leaves, with increasing Mg in the nutrient solution

from 0 to 192 mg L⁻¹, was not observed. This can probably be explained by the fact that even plants irrigated with a solution without Mg showed no symptoms of Mg deficiency, as inferred from chlorophyll concentrations and plant weights that were not significantly affected. In addition, the absence of symptoms of Mg deficiency in the treatment of 0 mg Mg L⁻¹ is probably related to the short duration of the experiment, combined with the excellent nutritional status of the plants at the beginning of the experiment (i.e., the pre-existing amount of Mg in the plant tissues did not have time to dilute much).

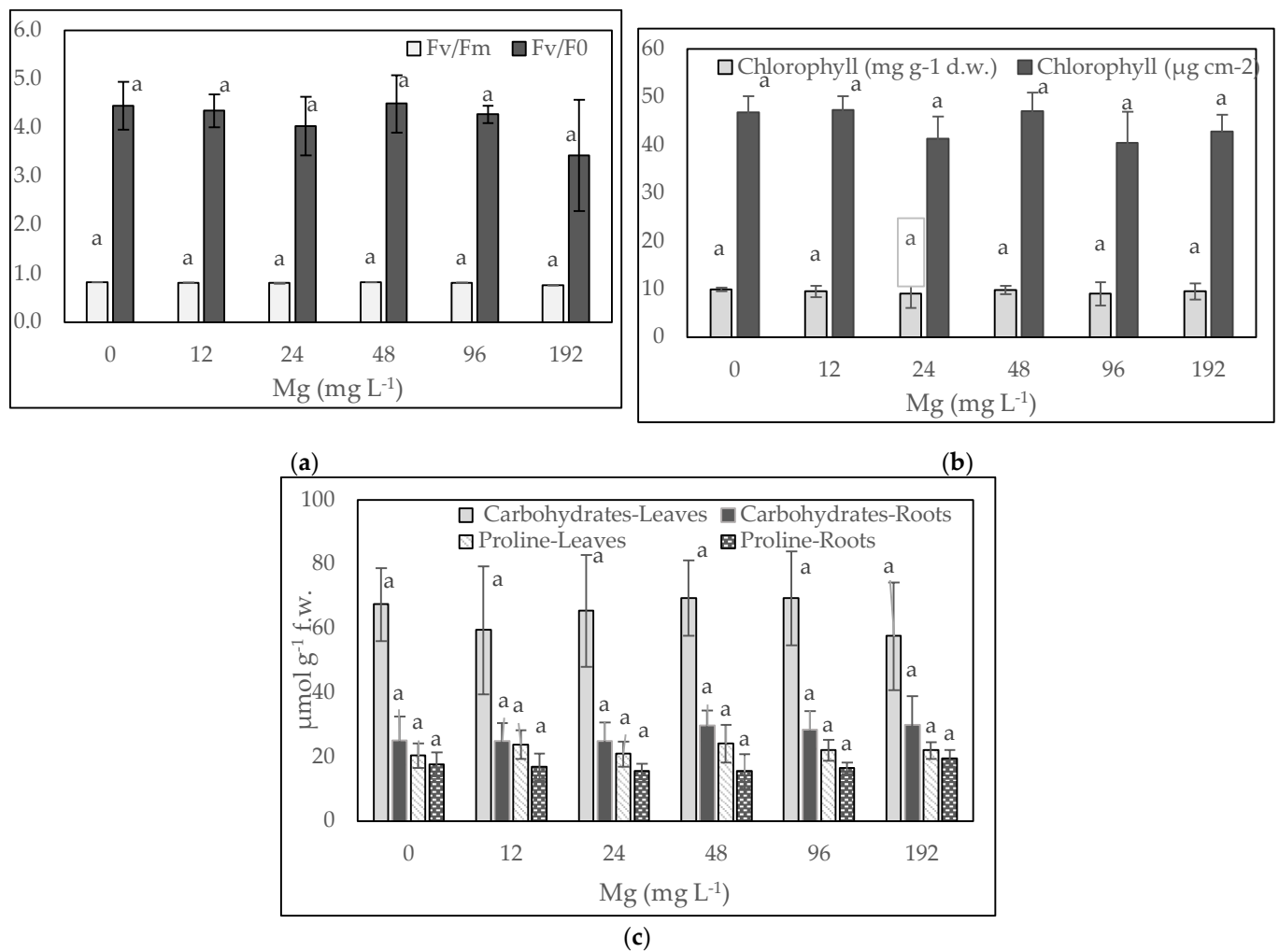


Figure 1. Effect of Mg concentration of the nutrient solution (0–192 mg L⁻¹) on (a) F_v/F_m, F_v/F₀ of leaves, (b) chlorophyll content of leaves, and (c) carbohydrate and proline content of leaves and roots of sweet orange plants. (All the values are the means of six replications ± S.D. Means followed by the same letter in the same column are not significantly different at $p < 0.05$ (Duncan's multiple range test, $n = 6$)).

It is well-known that a sufficient Mg supply is necessary for the photosynthetic absorption of CO₂ [43,54]. Since electrons and excitation energy not employed in photosynthetic processes produce excessive ROS generation in cell compartments, restricted absorption under magnesium deficiency is known to increase oxidative stress [43]. Proline contributes to the antioxidant protection of plants [55]. However, no significant interaction between the concentration of Mg in the nutrient solution and the concentration of proline in leaves and roots of the sweet orange plants was recorded (Figure 1c).

4. Conclusions

The findings of this study hold great importance for citrus growers. Despite administering a wide range of magnesium (Mg) concentrations (0–192 mg L^{−1}) through the nutrient solution, there were notable challenges in increasing Mg concentrations in various plant organs and the overall Mg absorption by the plants. These results not only provide an explanation for the sensitivity of sweet orange plants to Mg deficiency, but also highlight the presence of a root mechanism that strictly controls Mg absorption. Moreover, it was observed that changes in Mg concentration in the nutrient solution had a more positive impact on Mg concentrations in the scion's tissues, particularly in the leaves, compared to the rootstock's tissues. This finding offers some relief in addressing Mg shortage in sweet orange trees through soil fertilization. By applying fertilizers to the soil, growers can mitigate the difficulties associated with correcting Mg deficiency, particularly in the scion's tissues. Furthermore, the study reveals significant negative interactions between Mg availability in the rhizosphere and the total absorption of other nutrients, such as potassium (K), phosphorus (P), calcium (Ca), manganese (Mn), and iron (Fe), as well as their concentrations in the leaves (Ca). This highlights the need for careful attention to the dosages of Mg fertilizers applied, considering the potential impact on the availability and uptake of these other nutrients.

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