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The Response of Canola (*Brassica napus* L.) Cultivars to Different Soil K/Mg Ratios in Greenhouse Conditions

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ABSTRACT

To investigate the effects of different levels of available potassium (K) and magnesium (Mg), and their interactions, on the growth characteristics of canola cultivars, a factorial experiment was conducted using a completely randomized design (CRD) with three replications in a pot culture. The first factor consisted of five combinations of the K to Mg ratio (existing conditions, 80%, 90%, 110%, and 120% of the existing condition) by adding potassium or magnesium sulfate. The concentration of available K^+ and Mg^{2+} in the existing conditions of soil was 237 and 206 mg kg^{-1}, respectively (K^+/Mg^{2+} ratio 1.15). The second factor included three canola cultivars (Zafar, Dalgan, and Hyola50). After eight weeks (prior to flowering), the plants were harvested and shoot dry weight (SDW), the concentration of K, Mg, sodium (Na), and calcium (Ca) in the soil, shoots, and roots were measured. Based on the results, the Hyola50 cultivar preferred further amounts of K^+ to Mg^{2+} (110%). Still, the Dalgan cultivar preferred higher amounts of Mg^{2+} (90%) (10.8 and 9.6 gr pot^{-1} SDW, respectively, for Hyola50 and Dalgan). The highest K concentrations in the shoots of the Dalgan (5.10%) and Zafar (4.4%) cultivars were observed at the 120% ratio. The K concentration in the roots of all cultivars (0.928%) was lower than that in the shoots (4.13%). The Hyola50 cultivar demonstrated a greater need for K^+ than Mg^{2+} in the soil and was found to be less K-efficient compared to the Dalgan and Zafar cultivars. It is not suggested to maintain a consistent K^+/Mg^{2+} ratio in the soil for all canola cultivars.

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1. Introduction

Global production of rapeseed and canola seeds reached approximately 87.2 million tons in 2022 (FAO, 2024). After soybean and oil palm, canola (*Brassica napus L.*) ranks as the third-largest source of vegetable oil worldwide (Chew, 2020). Canola is the most significant oilseed crop, boasting the largest cultivated area among oilseed crops in Iran. This prominence is due to its adaptability to various conditions, economic value, and competitive pricing compared to cereals. In 2022, the cultivated area for canola in Iran was about 160,000 hectares, producing 300,000 tons with an average yield of 1,875 kg ha^{-1} (FAO, 2024). The primary objective for canola producers and breeders is to increase grain yield per unit area or to enhance oil yield and quality, both of which are strongly influenced by environmental conditions and the interaction between the environment and cultivars (Sabbahi *et al.*, 2023).

Effective and balanced nutrient management is essential to achieving maximum yield and improving quality. Nutrient imbalances, whether due to deficiencies, excesses, or toxic substances, can significantly impact canola's growth, development, and yield (Jones and Olson-Rutz, 2016).Magnesium (Mg) is one of the most critical nutrients for grain filling, as

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it plays a vital role in starch and protein synthesis and transport. It has been recognized alongside phosphorus as a key nutrient for grain filling (Gerendás and Führs, 2013). Adequate Mg availability extends the lifespan of the plant's green tissues, ensuring complete photosynthesis during the growth period. This promotes organic compound production, seed formation (number of seeds per pod), and seed filling (thousand-seed weight) (Geng *et al.*, 2021).

A pilot field survey of canola cultivation across various provinces in Iran revealed variability in the levels of magnesium and potassium in the soil. In some farms, the available Mg was lower than K, while in others it was higher or approximately equal (Nourgholipour *et al.*, 2022). Results from an on-farm canola nutrition project indicated that 28% of the surveyed fields had available Mg levels below 200 mg kg^{-1} or a K^+/Mg^{2+} ratio of less than one. According to Geng et al. (2024), the critical threshold for exchangeable Mg in soil for canola is 200 mg kg^{-1}, and canola demonstrates significant growth responses in soils where the K^+/Mg^{2+} ratio exceeds 2.

A review of the literature suggests that exchangeable Mg constitutes approximately 5% of total soil Mg, representing 4–20% of the cation exchange capacity. Exchangeable Mg is approximately 80% lower than exchangeable Ca but is typically higher than K, comprising up to 5% of the total exchangeable cations. Soluble Mg in the soil exists in equilibrium with exchangeable Mg (Menzies *et al.*, 2019). Based on these studies, plant-available Mg in soil should exceed the levels of available K. Some sources, however, report that the available Mg and K levels are equivalent in mg kg^{-1} (Sait, 2015), while others indicate that Mg is lower than available K (Cottenie, 1980).

Potassium plays a vital role in strengthening canola plants, enhancing their resistance to diseases, cold, and drought stress, and increasing the production of carbohydrates, starch, and oil (Hasanuzzaman *et al.*, 2018; Lohani *et al.*, 2020; Xu *et al.*, 2021). A deficiency in K not only reduces crop growth but also diminishes the plant's response to nitrogen (N) and phosphorus (P) fertilizers (Li *et al.*, 2022). Canola has a high demand for K, which interacts positively with N, zinc (Zn), and P. This nutrient is rapidly absorbed during the early growth stages, with the highest demand occurring during the flowering stage (Jones and Olson-Rutz, 2016). The interaction between K and Mg is significant, as increasing soil K levels can reduce plant uptake of Mg and Ca. Moreover, Mg is more sensitive to this interaction than Ca (Rhodes *et al.*, 2018; Xie *et al.*, 2021). The availability of K to plants depends on the amount of exchangeable K and the relative proportions of other exchangeable cations in the soil (Li *et al.*, 2018; Bell *et al.*, 2021). In many agricultural soils, the depletion of available K is associated with factors such as crop harvest, removal of plant residues, lack of crop rotation, and improper fertilization practices (Grzebisz *et al.*, 2012). Additionally, K deficiency can arise from imbalances in other cations, particularly Ca and Mg, relative to K. Such imbalances, especially in the K^+/Mg^{2+} relationship, can significantly affect nutrient balance and yield in canola cultivation (Rietra *et al.*, 2017).

Despite the importance of K and Mg in plant nutrition, there has been limited research on their optimal application rates and interactions. There is no consensus on the critical level of Mg or the ideal K/Mg ratio in the soil for efficient fertilizer management and maximum yield. This lack of agreement presents a significant challenge in providing the canola plant with appropriate fertilizer recommendations. This research aimed to evaluate the effect of the soil K^+/Mg^{2+} ratio on K and Mg concentrations in the plant and its subsequent impact on growth conditions before the flowering stage of canola.

2. Materials and methods

2.1. Soil sampling and characteristics

The soil used for this experiment was sampled from the Soil and Water Research Institute farm in Karaj, Alborz Province, Iran (longitude 50°57' E, latitude 35°45' N) at 0–30 cm depth. The collected soil was air-dried and sieved through a 4 mm mesh for planting purposes and a 2 mm mesh for physical and chemical analysis. Soil texture was measured according to Gee and Bauder (1986), organic carbon according to Nelson and Sommers (1996), available micronutrients according to Lindsay and Norvell (1978), calcium carbonate equivalent according to Loeppert and Suarez (1996), pH and electrical conductivity (EC) according to Page (1982), available potassium (K) and sodium (Na) based on Sparks et al. (1996) using the ELEA Flame Photometer; available P according to Olsen and Sommers (1982) (Table 1). The Mg concentration was measured based on Hanway and Heidel (1952). In this method, a ratio of 1:5 soil to extractant was used with a mixing time of 5 minutes. The pH value of the ammonium acetate extractant was equal to 8.2 and its concentration was one molar at a wavelength of 285 nm (Hanway and Heidel, 1952). The amount of Ca in the soil was measured in the same way using a wavelength of 422 nm by the Schimadzu AA-670 atomic absorption spectrophotometer**.**

Table 1. Some physical and chemical properties of the soil before planting

B	Mn	Zn	Fe	Mg	Ca	Cu	P	K
				(mg kg^{-1}) (ava.)				
0.5	5	0.76	2.56	206	4575	0.6	25	237
CCE	OC (%)	EC (dS m^{-1})	pH	Soil texture	sand	clay (%)	silt	S_{ava} (mg kg^{-1})
8.2	0.5	2.03	7.96	CL	36	28	36	23

CCE: Calcium carbonate equivalent, SP: saturation percent, CL: clay loam, OC: organic carbon, EC: electrical conductivity, ava.; available, pH_S: pH in saturated paste.

The soil characteristics did not pose any particular limitations for the growth of canola, and the essential nutrients were provided following the plant's requirements. After plant harvest, the soil sample was taken from each pot for measuring available K and Mg in the soil.

2.2. Experimental design and treatments

A factorial experiment was conducted under greenhouse conditions. The factors included five K to Mg ratios (existing conditions as the baseline ratio, and 80%, 90%, 110%, and 120% of the baseline ratio) and three spring-type canola cultivars (Zafar, Dalgan, and Hyola50) with three replications, resulting in 45 experimental units. Pre-experiment measurements indicated a 237 mg K^+ kg^{-1} and 206 mg Mg^{2+} kg^{-1} in the soil with a K/Mg ratio of 1.15. Fertilizer adjustments to obtain required treatments were imposed using potassium sulfate (43.2% K) at 0.328 and 0.163 g pot^{-1} for the 110% and 120% ratios, respectively. Magnesium sulfate (9.63% Mg) was applied at 1.777 and 2.802 g pot^{-1} for the 90% and 80% ratios, respectively.

2.3. Greenhouse cultivation

Polyethylene pots (22 cm height, 20 cm diameter) were filled with 3 kg of 4 mm-sieved soil. Seeds of three spring-type canola cultivars (Hyola50 as a hybrid, Zafar, and Dalgan as an open-pollinated) were obtained from the Seed and Plant Improvement Institute (SPII), Karaj, Iran. Each pot initially received eight seeds, thinned to three plants after germination. Each pot received 150 mg of nitrogen per kg of soil, divided equally between ammonium sulfate and urea to balance sulfur from K and Mg sulfate. Half of the nitrogen was applied before planting, with the remainder applied at the four-leaf stage (21 days after planting). Micronutrient supplementation: Pre-plant applications included Mn (manganese sulfate) (5 mg kg^{-1}), Zn (zinc sulfate) (5 mg kg^{-1}), B (boric acid) (2.5 mg kg^{-1}), and Fe (iron chelate, 7%) (5.5 mg kg^{-1}). Greenhouse temperatures were maintained at 22–20°C during the day and 20–18°C at night, with a 16-hour light and 8-hour dark photoperiod. The relative humidity was kept at 65%. Irrigation was carried out based on field capacity and pot weight loss.

2.4. Characteristics measured in the experiment

The characteristics measured in this study included shoot dry weight (SDW), root dry weight (RDW), chlorophyll value (SPAD), the RDW to SDW ratio, and the concentrations of Mg, Ca, K, and sodium in both shoot and root plant samples. Additionally, the concentrations of Mg, Ca, K, and Na in soil samples after harvest were analyzed. The efficiency of K and Mg utilization in the soil was calculated using Equation 1 (Damon and Rengel, 2007).

$$\text{Increase Efficiency} = \text{Final value of K or Mg (mg kg}^{-1}\text{)} - \text{Initial value of K or Mg (mg kg}^{-1}\text{)} / \text{K or Mg applied (mg kg}^{-1}\text{)} \quad (1)$$

2.5. Measurements and analysis

Leaf chlorophyll value was measured using a SPAD-502 before harvest. Plants were harvested on the 55th day after planting (growth stage 50, pre-flowering; Bleiholder *et al*., 2001). Roots were carefully separated and washed with distilled water. Plant material was dry-ashed at 450°C for 10 hours to prepare extracts. Nutrient concentrations were measured as follows: K and Na using the ELEA flame photometer, and Ca and Mg using the Shimadzu AA-670 atomic absorption spectrophotometer at wavelengths of 422.7 nm and 285.2 nm, respectively.

2.6. Statistical analysis

The average effects of treatments on the measured properties were determined using analysis of variance

(ANOVA). Tukey's test was applied at a 5% probability significance level ($P<0.05$) to identify statistically significant differences among treatment means. Results of Tukey's test were reported for statistically significant properties based on the F test in the ANOVA table. Statistical analyses were performed using SAS v. 9.1 (SAS Institute, USA), and graphs were generated using Excel 2013.

3. Results and discussion

3.1. Effects of cultivars and K/Mg ratios on shoot and root dry weight and leaf chlorophyll

Analysis of variance (Table 2) revealed that the interaction between cultivar and fertilizer was statistically significant ($P<0.01$) for shoot dry weight (SDW), root dry weight (RDW), and the RDW/SDW ratio. The main effect of the cultivar was also found to significantly influence ($P<0.01$) the leaf chlorophyll SPAD value.

Table 2. Analysis of variance of the measured morphological traits of the canola cultivars

S.o.V.	d.f.	RDW	SDW	RDW/SDW	Chlorophyll (SPAD)
Cultivar (C)	2	0.43**	6.83**	0.003**	215.93**
Fertilizer (F)	4	0.23**	7.22**	0.0007^{ns}	16.47^{ns}
C × F	8	0.24**	4.09**	0.001**	19.79^{ns}
Error	30	0.046	1.07	0.0003	14.7
C.V. (%)	-	22	11.7	18	7.4

**and * indicate the statistical significance at the levels of 1 and 5%, and ^{ns} indicates no significant.

The interaction effect of fertilizer levels on SDW in canola cultivars is depicted in Fig. 1a. For the Hyola50 cultivar, the maximum SDW was observed at the 110% fertilizer rate, and was significantly higher than the SDW at other rates. The lowest SDW for this cultivar occurred at the 80% fertilizer level, showing a significant difference compared to the 110% level. In the Dalgan cultivar, the highest SDW was recorded at the 90% fertilizer level, while the lowest SDW was observed at the 120% level. For the Zafar cultivar, the highest SDW was associated with the current fertilizer level, and increasing the potassium level to 120% did not result in any further increase in SDW. Among the three cultivars, the lowest SDW was recorded for the Dalgan cultivar at the 120% fertilizer level, while the highest SDW was achieved by the Hyola50 cultivar at the 110% level (Fig. 1a).

The Hyola50 cultivar had the highest root dry weight (RDW) at the 110% fertilizer level, which was significantly more than the RDW observed at the 80% fertilizer level. This pattern was also seen for SDW of this cultivar. In contrast, the Dalgan cultivar displayed the highest RDW at the 90% fertilizer level, with the lowest RDW recorded at the 120% level. Zafar cultivar showed the highest RDW at the 110% fertilizer level, but variations in potassium levels did not lead to significant changes in RDW for this cultivar. Among the three cultivars, the lowest RDW was seen in Dalgan at the 120% fertilizer level, while the highest RDW was observed in Hyola50 at the 110% level (Fig. 1b).

The ratio of RDW/SDW varied across cultivars and fertilizer levels. In the Hyola50 cultivar, the highest RDW/SDW ratio was observed at the 110% fertilizer level, while the lowest ratio was recorded at the 80% level, showing a significant difference from the 110% level. For the Dalgan cultivar, the highest RDW/SDW ratio occurred at the 90% fertilizer level, and the lowest ratio was observed at the 120% level. Similarly, the Zafar cultivar exhibited the highest RDW/SDW ratio at the 110% level, but an increase in K levels to 120% did not significantly affect this ratio. Among all cultivars, the lowest RDW/SDW ratio was recorded for Dalgan at the 120% level, while the highest ratio was observed for Hyola50 at the 110% level (Fig. 1c).

The study evaluated the effects of cultivars and the potassium-to-magnesium (K^+ /Mg^{2+}) ratio in soil on shoot and root dry weight, as well as leaf chlorophyll SPAD value. The shoot and root dry weights (SDW and RDW) of three canola cultivars showed distinct responses to varying levels of potassium (K) and magnesium (Mg) availability in the soil. Additionally, the root-to-shoot dry weight ratio (SDW/ RDW) for these cultivars displayed differential responses to K and Mg concentrations, with trends similar to those observed in RDW (Fig. 1). The Hyola50 cultivar had the highest RDW and SDW at the 110% fertilizer level. In contrast, the Dalgan cultivar displayed the highest RDW at the 90% fertilizer level. These cultivar-specific variations in response to different K^+ /Mg^{2+} ratios may be attributed to the unique physiological and metabolic requirements of each cultivar for these essential nutrients.

A study by Damon et al. (2007) highlighted that canola genotypes responded differently to different levels of K availability (each genotype preferred a different amount of K). The efficiency of K uptake was found to be influenced by both genotypic differences in the uptake and utilization of K. The authors suggest that genotypes exhibiting high K-efficiency could potentially be utilized in soils deficient in K. The efficiency of K uptake can be explained by two factors: (i) the ability to effectively absorb K from the soil (uptake efficiency) and/or (ii) the capacity to efficiently utilize K within the plant. In terms of K utilization efficiency, genotypes may differ in their ability to transport K at the cellular or whole-plant level or substitute K^+ with other osmolytes, such as NO_3^-, soluble sugars, or amino acids. Regarding uptake efficiency, genotypes may exhibit differences in root morphological traits (e.g., root length, root turnover rate, or the number and length of root hairs) or physiological traits (e.g., capacity for high-affinity K uptake or the ability to alter K availability in the rhizosphere) (Damon *et al.*, 2007).

Our findings indicated that the Hyola50 cultivar required a higher amount of K for optimal SDW (Fig. 1a). In contrast, the Dalgan and Zafar cultivars showed a preference for higher Mg levels, possibly due to their ability to maintain high shoot weight even under K-deficient conditions, along with their capacity to allocate biomass more heavily to the shoot during K deficiency stress. This observation is supported by previous studies conducted by Damon et al. (2007) and Damon and Rengel (2007), which found that K deficiency reduced shoot dry weight in both canola and wheat. Additionally, Ahmed et al. (2015) reported that canola cultivars exhibited different responses to the rates of applied K.

The observed growth enhancement due to Mg fertilization may be linked to the low extractable Mg levels in the soil, which could also be influenced by high levels of extractable K. Geng et al. (2021) indicated that reduced Mg uptake, caused by low plant-available Mg and high extractable K, is a key soil factor contributing to Mg deficiency in plants. A distinct early response to Mg deficiency in plants is the noticeable shrinkage of the root system and a reduced root-to-shoot dry weight ratio, resulting from limited photosynthate transport from source leaves to sink organs. When Mg is supplied in adequate amounts, deficiency symptoms are suppressed, leading to improved root biomass and subsequent increases in shoot biomass (Ishfaq *et al.*, 2022). In our study, SDW showed a positive and significant correlation with RDW ($R^2 = 0.63^{**}$).

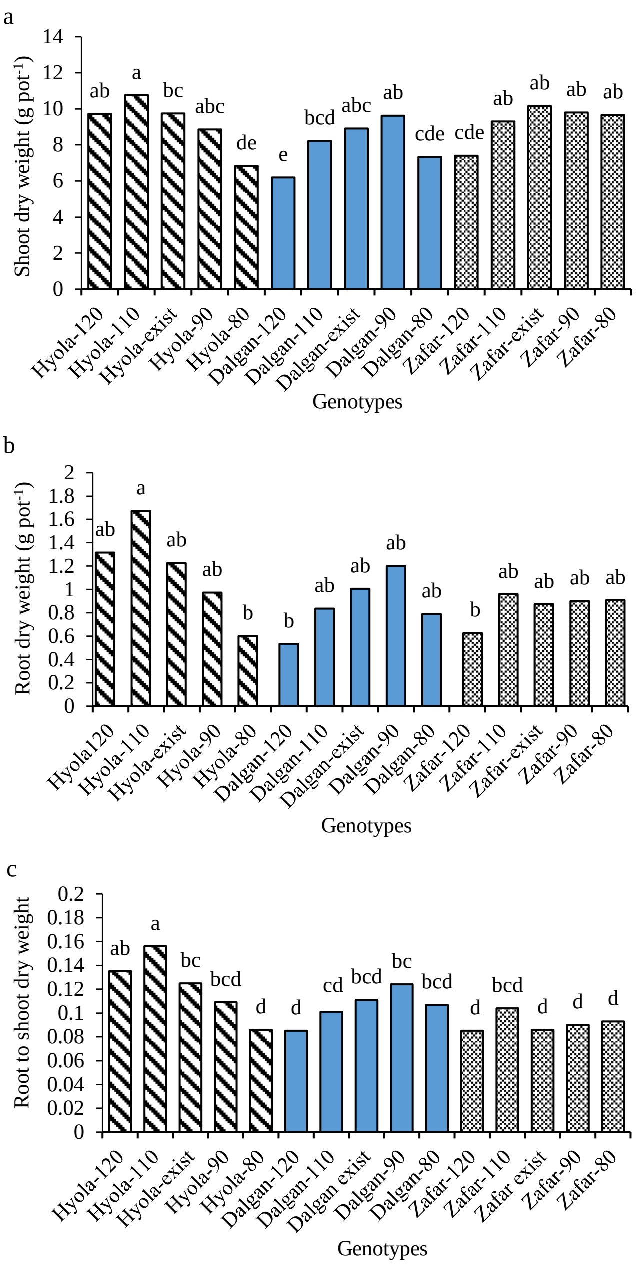

Figure 1. Response of canola cultivars to different K^+ /Mg^{2+} ratio in the soil. a) shoot dry weight, b) root dry weight, and c) root to shoot dry weight. The existing condition of K^+ /Mg^{2+} in the tested soil was 1.15 (206/237 mg kg^{-1}). This includes the initial amount as well as increases of 80%, 90%, 110%, and 120% of the existing condition. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test

Regarding chlorophyll SPAD value, the Zafar cultivar demonstrated a significantly lower average chlorophyll value (47.65 SPAD) compared to the Hyola50 (54.9 SPAD) and Dalgan (53.23 SPAD) cultivars. The difference in chlorophyll value between Hyola50 and Dalgan was not statistically significant (Fig. 2). This suggests that the Hyola50 and Dalgan cultivars have a higher photosynthetic efficiency due to their higher chlorophyll value. Magnesium-deficient leaves often exhibit sub-optimal photosynthetic CO_2

assimilation due to a lower abundance of chlorophyll, impaired critical enzymes, and an over-accumulation of photosynthates in the leaves. This has been observed in various plant species in different growth conditions with limited Mg (Ishfaq *et al.*, 2022). The amount of chlorophyll value in plants is a significant factor in maintaining photosynthetic capacity (Farahani *et al.*, 2020). Studies have shown that different cultivars of canola (5 cultivars) have different levels of chlorophyll value during the vegetative growth stage (GS: 1.09, 40 days) (Rose *et al.*, 2007) and pod formation (Farahani *et al.*, 2020). Plants that receive sufficient K tend to produce more photosynthetic material compared to those with low K levels (Rawat *et al.*, 2022). The results of Bandehagh et al. (2015) indicate that differences in cultivars can influence chlorophyll values. There is a direct correlation between the concentration of Mg in plant tissue and the synthesis of chlorophyll (Choudhury *et al.*, 2022). Increasing the amount of chlorophyll through enhanced photosynthesis (Fathi, 2022) leads to an increase in shoot dry weight, as seen in the results of the Hyola50 cultivar in the present study (Fig. 2).

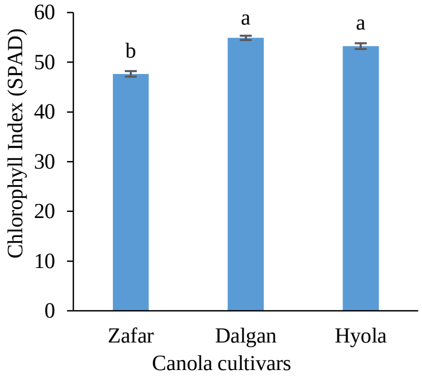

Figure 2. Comparison of canola cultivars for the chlorophyll SPAD value of leaves. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test (SE, n = 15).

3.2. Effects of treatments on the concentration of nutrients in the shoot

Based on the results of the analysis of variance (Table 3), highly significant interaction effects ($p<0.01$) were observed between cultivar and fertilizer factors on the K concentration of canola shoots. Furthermore, significant effects of the canola cultivar and fertilizer were also noted on the Na and Mg concentrations, as well as the ratio of K/Mg concentration in the shoot. However, the main effect of the cultivar and fertilizer on the Ca concentration in the shoots was not found to be significant.

Table 3. Results of the analysis of variance for nutrient concentration in canola shoots

S. o. V.	d.f.	Ca	Mg	Na	K	K/Mg ratio in shoot
Cultivar (C)	2	0.49^{ns}	0.036^{**}	0.021^{**}	2.42^{**}	49.1^{**}
Fertilizer (F)	4	0.35^{ns}	0.018^{**}	0.013^{*}	0.48^{ns}	15.8^{*}
C × F	8	0.2^{ns}	0.001^{ns}	0.006^{ns}	0.7^{**}	7.1^{ns}
Error	30	0.19	0.002	0.003	0.2	4.04
C.V. (%)	-	15.3	13.4	21.4	10.9	17.5

**and * indicate the statistical significance at the levels of 1 and 5%, and ^{ns} indicates no significant.

There was a significant difference in shoot K concentration among the canola cultivars ($P<0.01$). Specifically, the Dalgan cultivar had a significantly higher K concentration (4.57%) in the shoots compared to the Hyola50 cultivar (4.05%) and Zafar cultivar (3.77%). However, there was no significant difference in K concentration in the aerial parts of Hyola50 and Zafar cultivars. The Dalgan cultivar had the highest K concentration in its aerial parts with a ratio of 120% K to Mg (5.10%). Interestingly, there was no significant difference in K concentration among the different fertilizer levels in the Dalgan cultivar (Table 4). Similarly, the Zafar cultivar had its highest K concentration at the 120% fertilizer ratio (4.4%). In contrast, the Hyola50 cultivar had its highest K concentration at the 80% fertilizer ratio (4.86%) and it is the lowest at the 110% ratio (3.23%). This difference was significant in the Hyola50 cultivar for shoot K concentration. Overall, the Hyola50 cultivar had the lowest K concentration among all the treatments and cultivars at the 110% fertilizer level.

The highest magnesium (Mg) concentration in the shoot was recorded at the 80% fertilizer ratio (0.43%), which was significantly different from both the current level and the 110% and 120% fertilizer ratios (Fig. 3a). The highest K/Mg ratio in the shoot was observed at the 120% fertilizer ratio (12.81), which was not significantly different from the 110% level, but showed a significant difference when compared to the 80% level (Fig. 3b).

At the current fertilizer level, the shoot had the highest sodium (Na) concentration (0.33%), but with the addition of K and Mg fertilizers, the Na concentration decreased, reaching its lowest value at the 110% fertilizer ratio (0.24%) (Fig. 3c).

Table 4. The interaction effects of cultivar and K^+ to Mg^{2+} ratio in the soil on K, Ca, and Mg concentration in the roots and K concentration in the shoots of canola

Cultivar	K^+ to Mg^{2+} ratio in soil	K con. in shoot	K con. in root	Mg con. in root	Ca con. in root	K to Mg ratio in root
		%				
Dalgan	current	4.42^{abcd}	0.87^{ab}	0.16^{abc}	2.63^{ab}	5.54^{ab}
Dalgan	110	4.62^{abc}	0.98^{ab}	0.19^{abc}	2.43^{b}	5.28^{ab}
Dalgan	120	5.10^{a}	0.87^{ab}	0.13^{bc}	1.65^{b}	6.78^{ab}
Dalgan	80	4.54^{abcd}	0.90^{ab}	0.2^{abc}	2.76^{ab}	4.73^{ab}
Dalgan	90	4.16^{abcd}	0.87^{ab}	0.22^{a}	2.86^{ab}	4.12^{b}
Hyola50	current	3.96^{abcd}	0.69^{b}	0.17^{abc}	2.93^{ab}	4.06^{b}
Hyola50	110	3.23^{d}	0.68^{b}	0.19^{abc}	4.03^{a}	4.03^{b}
Hyola50	120	3.90^{abcd}	0.73^{ab}	0.19^{abc}	4.1^{a}	3.76^{b}
Hyola50	80	4.86^{ab}	1.04^{ab}	0.12^{c}	1.72^{b}	9.09^{a}
Hyola50	90	4.32^{bcd}	0.87^{ab}	0.17^{abc}	2.7^{ab}	5.11^{ab}
Zafar	current	3.72^{bcd}	1.06^{ab}	0.21^{ab}	2.67^{ab}	5.46^{ab}
Zafar	110	3.77^{abcd}	1.13^{a}	0.19^{abc}	2.05^{b}	6.07^{ab}
Zafar	120	4.40^{abcd}	1.24^{a}	0.16^{abc}	2.27^{b}	7.98^{ab}
Zafar	80	3.34^{cd}	0.96^{ab}	0.21^{abc}	2.51^{ab}	4.74^{ab}
Zafar	90	3.64^{bcd}	1.03^{ab}	0.22^{a}	2.55^{ab}	4.86^{ab}

The current level of K^+/Mg^{2+} in the tested soil is 1.15 (206/237). This includes the initial amount as well as 80%, 90%, 110%, and 120% of the current state. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test.

The Dalgan cultivar exhibited the highest Na concentration in the shoots (0.31%), which was not significantly different from Hyola50 (0.27%), but was significantly higher than Zafar (0.23%) (Fig. 4a). No significant difference was found between the Zafar and Dalgan cultivars in terms of Mg concentration (Fig. 4b). Hyola50, however, had a significantly higher K concentration in the shoots (0.43%) compared to Dalgan (0.36%) and Zafar (0.33%). Additionally, Hyola50 had the lowest K/Mg ratio in the shoots (9.48%), which was significantly different from both Dalgan (12.98%) and Zafar (12.01%). However, the difference between the Dalgan and Zafar cultivars for the ratio of K /Mg in the shoots was not significant at the 5% level (Fig. 4c). Different cultivars have varying concentrations of K and respond differently to the ratio of K and Mg applied. For example, a study by Rose et al. (2007) found that different cultivars of canola (three cultivars) had K concentrations ranging from 4-5% during the vegetative growth stage (GS: 1.09, 40 days). It is important to note that within each species, there are numerous cultivars. Breeders are constantly developing new cultivars with higher yields, increased stress tolerance, and greater appeal to consumers. These new cultivars may also exhibit significant variations in nutrient concentrations, necessitating different fertilization techniques (Korzeniowska and Stanislawska-Glubiak, 2022). These differences in nutrient content can be attributed to both genetic and environmental factors (Broadley *et al.,* 2008). Specifically, the highest concentration of Mg in the shoots was observed when the fertilizer ratio was set at 80% (Fig. 3a). This boost in Mg levels was a direct result of the application of Mg fertilizer.

Additionally, the highest ratio of K to Mg in the shoots was observed at a fertilizer ratio of 120%, which was not significantly different from the 110% ratio but differed significantly from the 80% and 90% ratios (Fig. 3). Moreover, the addition of K and Mg fertilizers resulted in a decrease in sodium concentration in the shoots, with the lowest concentration noted at a fertilizer ratio of 110% (0.24%). It seems that K fertilizer has a more pronounced effect on reducing sodium levels in the shoots compared to Mg fertilizer, which could be crucial in alleviating the impacts of salt stress. Interestingly, the Dalgan cultivar exhibited the highest sodium concentration in the aerial parts (0.31%), which was not significantly different from the Hyola50 cultivar (0.27%) but significantly different from the Zafar cultivar (0.23%) (Fig. 4). Regarding nutrient requirements, the Hyola50 cultivar demonstrated a higher demand for K compared to Mg in order to achieve the proper dry-weight ratio. On the other hand, the Zafar and Dalgan cultivars required more Mg than K. This highlights the importance of considering the ratio of K to Mg, rather than just focusing on individual nutrient levels. This was also observed in a study by Brennan et al. (2007), where two canola cultivars (Outback and Karoo) showed significant increases in seed yield when given calcium. The cultivar Outback was found to be more sensitive to calcium deficiency compared to the other cultivars. The critical calcium concentration for young wheat (GS15) and canola (GS1.5) shoots, which is related to 90% of the maximum grain yield, was 0.33% for wheat and 2.5% for both canola cultivars.

3.3. Effects of treatments on nutrient concentration in the root

According to the results of the analysis of variance (Table 5), there was a significant interaction effect between cultivar and fertilizer on the concentration of K ($p<0.05$), Mg ($p<0.05$), Ca ($p<0.01$), and the ratio of K/Mg in canola roots ($p<0.01$). Additionally, the main effect of the canola cultivar on root Na concentration was also significant ($p<0.01$).

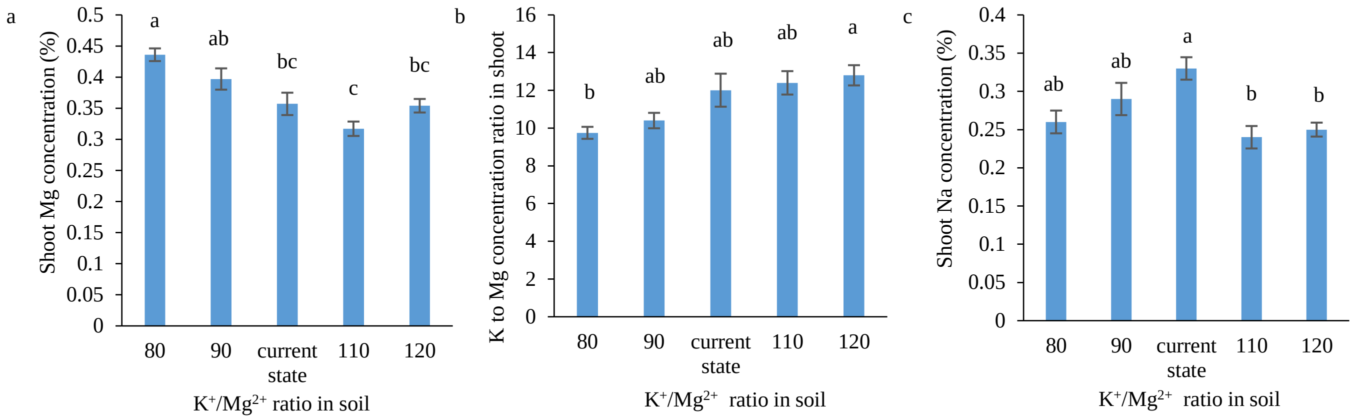

Figure 3. The main effect of K^+/Mg^{2+} ratio in the soil on the concentration of a) Mg, b) the ratio of K /Mg and c) Na in canola shoot. The current level of K^+/Mg^{2+} in the tested soil was 1.15 (206/237). This includes the initial amount as well as increases of 80%, 90%, 110%, and 120% of the current state. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test (SE, n = 9).

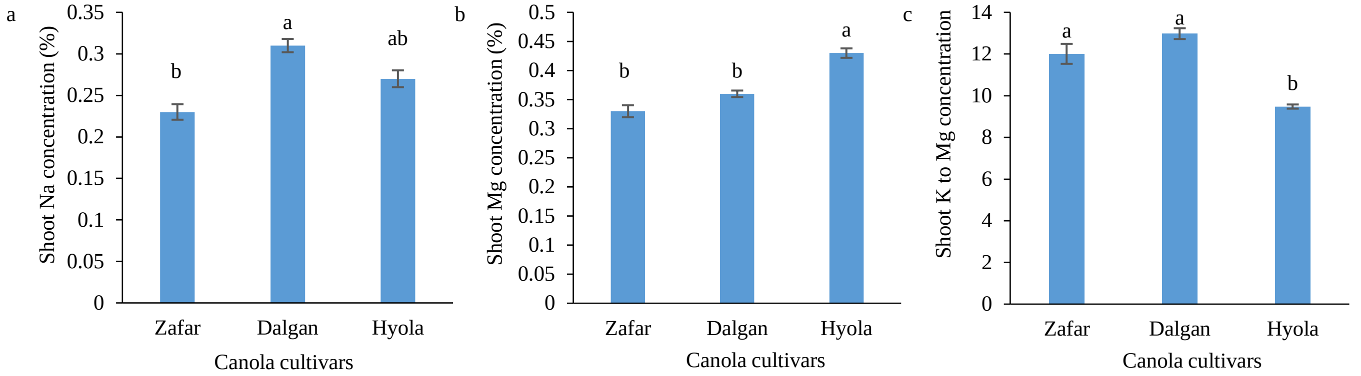

Figure 4. The canola cultivars differ in the concentration of a) Na, and b) Mg in the shoot, and c) the ratio of K /Mg in the shoot. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test (SE, n =15).

Table 5. The analysis of variance of nutrient concentration in canola root

S.o.V.	d.f.	Ca	Mg	Na	K	K /Mg in root
Cultivar (C)	2	2.17^{**}	0.0027^{ns}	0.005^{**}	0.31^{**}	1.66^{ns}
Fertilizer (F)	4	0.331^{ns}	0.0022^{ns}	0.0005^{ns}	0.01^{ns}	4.34^{ns}
C × F	8	1.176^{**}	0.0026^{*}	0.0008^{ns}	0.05^{*}	9.37^{**}
Error	30	0.285	0.0008	0.0006	0.016	2.19
C.V. (%)	-	20	16	15	14	27

**and * indicate the statistical significance at the levels of 1 and 5%, and ^{ns} indicates no significant.

In the root tissue, the average potassium (K) concentration of the Zafar cultivar (1.08%) was significantly higher than that of the Dalgan (0.9%) and Hyola50 (0.8%) cultivars (Table 4). However, there was no significant difference between the K concentrations of the Dalgan and Hyola50 cultivars. The highest K concentration in canola roots was observed in the Zafar cultivar at 1.24% (120% fertilizer level), which was significantly higher than the 1.10% found in the Hyola50 cultivar at the same fertilizer level. In Hyola50, the lowest K concentration was recorded at the 110% fertilizer level (0.68%), significantly lower than the concentration at the 80% fertilizer level (1.04%). For the Dalgan cultivar, the highest K concentration (0.98%) was achieved at the 110% fertilizer level, with no significant differences observed across other fertilizer levels (Table 4). In both the Zafar and Dalgan cultivars, the highest root Mg concentration was observed at the 90% fertilizer level (0.22%) (Table 4). This was significantly higher than the Mg concentration at the 120% fertilizer level in the Dalgan cultivar (0.13%). The lowest root Mg concentration in the Hyola50 cultivar was recorded at the 80% fertilizer level (0.12%).

The highest Ca concentration in the Hyola50 cultivar was found at the 120% fertilizer level (4.1%), which was significantly higher than the concentration at the 80% fertilizer level (1.72%) (Table 4). In the Dalgan cultivar, the highest Ca concentration (2.86%) was recorded at the 90% fertilizer level, although this was not significantly different from other fertilizer levels in the cultivar. Similarly, the highest Ca concentration in the Zafar cultivar (2.67%) occurred at the current fertilizer level, with no significant differences observed across other levels in this cultivar.

The highest K/Mg ratio was observed in the Hyola50 cultivar at the 80% fertilizer level (9.09%) (Table 4), which was significantly higher than the ratios at the 120%, 110%, and current fertilizer levels in this cultivar. The lowest K/Mg ratio in Hyola50 was found at the 120% fertilizer level (3.76%). In the Zafar cultivar, the highest K/Mg ratio (7.98%) was obtained at the 120% fertilizer level, with no significant differences observed across other fertilizer levels in this cultivar. Similarly, the highest K/Mg ratio in the Dalgan cultivar (6.78%) was found at the 120% fertilizer level, with no significant differences between this and other fertilizer levels in the cultivar.

Sodium concentration in the roots of the Zafar and Dalgan cultivars was 0.18%, significantly higher than that of the Hyola50 cultivar (0.15%).

Potassium (K) concentration in the roots of the cultivars was found to be lower than that in the shoots, with significant differences in K levels among the cultivars. The Zafar cultivar exhibited a 12.5% higher K concentration in the roots compared to the Dalgan cultivar and a 35% higher concentration compared to the Hyola50 cultivar (Table 4). Conversely, the Dalgan cultivar had the highest K concentration in the shoots. These results suggest that the Zafar cultivar retains more K in the roots, resulting in reduced translocation to the aerial parts compared to the other two cultivars. Notably, the K concentration in the roots and shoots of the Hyola50 cultivar differed significantly from that of the other two cultivars.

Potassium plays a vital role in the metabolism of nucleic acids, proteins, vitamins, and growth-related substances, which in turn influence the metabolites and growth processes of plant tissues. Additionally, K enhances photosynthesis and can significantly affect overall plant growth and development (Réthoré *et al.*, 2021; Tariq *et al.*, 2023). As K availability in the soil increases, its absorption by plants also increases, leading to a decrease in the K/Mg ratio in the roots (Hu *et al.*, 2021). In this study, the Hyola50 cultivar had the lowest K concentration in the shoots, while both the Zafar and Dalgan cultivars showed an increasing trend in K concentration in the shoots.

Regarding magnesium concentration in the roots, both the Zafar and Dalgan cultivars had the highest Mg concentration at the 90% fertilizer level (0.22%), whereas the lowest concentration was observed at the 80% fertilizer level (0.12%). This trend was distinct from that observed in the other cultivars (Table 4). The highest K/Mg ratio in the roots was recorded in the Hyola50 cultivar at the 80% fertilizer level (9.09%). In contrast, the Zafar cultivar exhibited the highest ratio at the 120% fertilizer level (7.98%), while the Dalgan cultivar showed the highest ratio at the same fertilizer level (6.78%). These findings suggest that the Hyola50 cultivar responds differently to K/Mg ratios in the roots compared to the other cultivars.

In terms of sodium concentration, the roots of the Zafar and Dalgan cultivars contained 0.18%, which was significantly higher than the 0.15% observed in the Hyola50 cultivar. This behavior contrasts with that of the other two cultivars in terms of K concentration. Root growth appears to be positively influenced by calcium concentration in the roots, followed by Mg concentration. Additionally, an increase in the K^+/Mg^{2+} ratio in the soil results in a decrease in root growth.

3.4. Effects of treatments on available Mg^{2+} and K^+ concentrations in the soil and nutrient efficiency

Based on the results presented in Table 6, the fertilizer treatment was the only factor that had a significant effect on the available concentrations of K^+ and Mg^{2+} in the soil, as well as the K^+/Mg^{2+} ratio ($p<0.01$). Neither the cultivar nor the interaction between fertilizer and cultivar had a significant impact on these indices.

Table 6. Analysis of variance result for available K^+ and Mg^{2+} in the soil

S.o.V.	d.f.	Mg	K	K^+/Mg^{2+} in soil
Cultivar (C)	2	1737.11^{ns}	1303.17^{ns}	0.0077^{ns}
Fertilizer (F)	4	48814.8**	7721.42**	0.189**
C × F	8	1586.94^{ns}	764.95^{ns}	0.0172^{ns}
Error	30	7778.61	1630.98	0.2755
C.V. (%)	-	20	12	22

** **and * indicates the statistical significance at the levels of 1 and 5%, and ^{ns} indicates no significant

The highest concentration of available K^+ in the soil was observed at the 120% fertilizer level (373 mg kg^{-1}), which was significantly greater than the concentrations at the 80%, 90%, and current fertilizer levels ($p<0.05$) (Fig. 5a). In contrast, the highest concentration of available Mg^{2+} in the soil was obtained at the 80% fertilizer level (545 mg kg^{-1}), significantly different from the current level and the 110% and 120% fertilizer treatments (Fig. 5b). The highest K/Mg ratio was observed at the 120% fertilizer level (0.922), which did not significantly differ from the 110% and current levels but was significantly higher than the 80% and 90% levels. At the 80% fertilizer level, the K/Mg ratio decreased to 0.6.

The highest soil K^+ concentration was achieved at the 120% fertilizer level (373 mg kg^{-1}) (Fig. 5a), while the highest available Mg concentration in the soil was observed at the 80% fertilizer level (545 mg kg^{-1}). Based on shoot dry weight (SDW) and root dry weight (RDW) data, the Hyola50 cultivar demonstrated a better response to increasing K^+ levels in the soil, indicating a higher requirement for K^+ than Mg^{2+} for optimal growth. However, the results suggest that a uniform K^+/Mg^{2+} ratio in the soil cannot be recommended for all canola cultivars to achieve optimal growth (Fig. 5c).

Previous studies (Nourgholipour *et al.*, 2018) have shown that the Hyola50 cultivar is efficient in phosphorus uptake but appears to be less efficient in K nutrient uptake and utilization. Therefore, ensuring sufficient K levels in regions with K-deficient soils is crucial when planting this cultivar, which is widely cultivated in both humid and dry warm regions of Iran. Field surveys across the country have indicated a decrease in available K in many areas, with K deficiency being the second most common macronutrient deficiency after P (Nourgholipour *et al.*, 2022).

The amount of available Mg in the soil correlated significantly (0.19^*) with Mg concentration in the shoots, but no significant correlation was observed between Mg and K concentrations in the roots. Similarly, the available K^+ in the soil did not show a significant correlation with nutrient concentrations in the shoots or roots, including root K concentration. Additionally, root K concentration did not correlate significantly with shoot K concentration, and root Mg concentration had no significant correlation with shoot Mg concentration.

The addition of K fertilizer at the 120% and 110% treatment levels resulted in an increased K/Mg ratio. It is noteworthy that Mg is typically absorbed in smaller quantities than K, but competition between cations during absorption can lead to Mg deficiency in plants (Gerendás and Führs, 2013; Xie *et al.*, 2021). This competition may also increase the amount of Mg in seeds, as K ions facilitate the transfer of Mg ions to storage organs such as seeds (Xie *et al.*, 2021). Further research is needed to examine the response of canola cultivars to Mg and K during the flowering and maturity stages of growth.

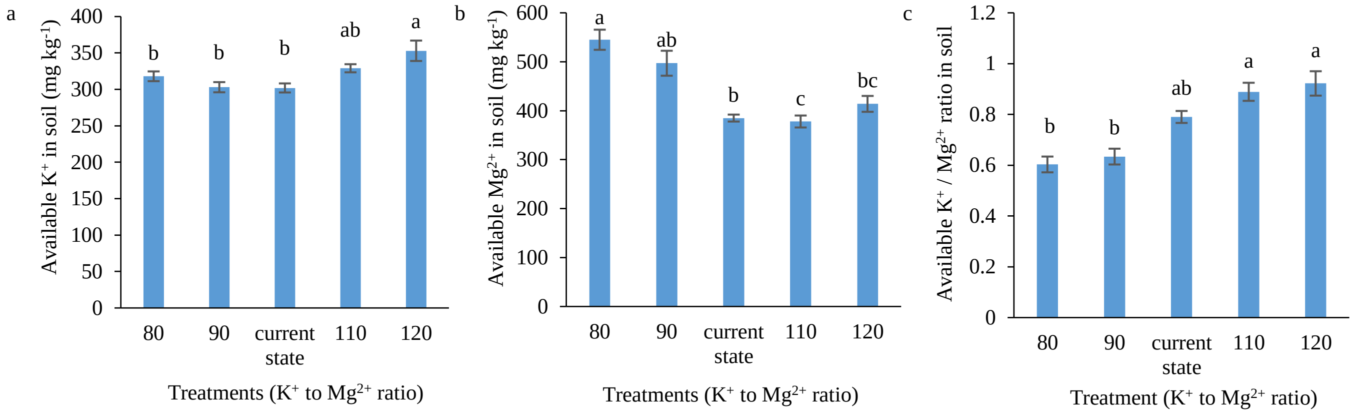

Figure 5. Main effect of fertilizer levels on the amount of soil available K^+, Mg^{2+}, and the ratio of these nutrients after harvest. The current level of K^+/Mg^{2+} ratio in the tested soil was 1.15 (206/237). This includes the initial amount as well as increases of 80%, 90%, 110%, and 120% of the current state. Columns with at least one common letter do not show a significant difference at the 5% level according to Tukey´s test (SE, n = 9).

Regarding nutrient efficiency, at higher applied K levels (120% or 47.5 mg K kg^{-1}), the efficiency of the increase in available K was greatest in the Zafar cultivar (2.156), followed by Dalgan (1.574) and Hyola50 (0.804) cultivars. At the lower applied K level (110% or 23 mg K kg^{-1}), the efficiency of increase was greatest in the Dalgan cultivar (1.446), followed by Hyola50 (1.188) and Zafar (0.921) cultivars (Table 7).

The efficiency of nutrient uptake, as indicated in Table 7, showed that for every mg K kg^{-1} of soil, the Zafar cultivar demonstrated an increase of 2.156 mg K kg^{-1} of soil. At lower K application rates (110% or 23 mg K kg^{-1} of soil), this increase was reduced to 1.446 mg K kg^{-1} of soil. These findings suggest that the efficiency of K uptake is influenced by both the applied K fertilizer rate and the specific canola cultivar.

For magnesium, at the higher applied Mg level (80% or 67 mg Mg kg^{-1}), the efficiency of the increase in available Mg was highest in the Hyola50 cultivar (2.923), followed by Dalgan (2.208) and Zafar (2.021) cultivars. At the lower applied Mg level (90% or 57 mg Mg kg^{-1}), the efficiency of increase was again greatest in the Hyola50 cultivar (2.418), followed by Dalgan (1.188) and Zafar (1.572) cultivars (Table 7). For Mg, increasing the fertilizer application rate enhanced the uptake efficiency, with the Hyola50 cultivar surpassing the Dalgan and Zafar cultivars at both the 80% and 90% fertilizer levels.

Table 7. Efficiency of increase for available K^+ and Mg^{2+} in the soil

Cultivar	K^+/ Mg^{2+} in soil	K efficiency	K^+/ Mg^{2+} in soil	Mg efficiency
Zafar	120%	2.156	90%	1.572
Dalgan	120%	1.574	90%	1.864
Hyola50	120%	0.804	90%	2.412
Zafar	110%	0.921	80%	2.021
Dalgan	110%	1.446	80%	2.208
Hyola50	110%	1.188	80%	2.923

4. Conclusion

The shoot dry weight (SDW) and root dry weight (RDW) of three cultivars showed varying responses to the availability of potassium (K) and magnesium (Mg) in the soil. It appears that K fertilizer has a greater impact than Mg fertilizer in reducing Na levels in the shoot. The correlation between SDW and the concentrations of calcium (Ca), K, and the potassium-to-magnesium (K^+/ Mg^{2+}) ratio suggests that, for optimal SDW production, potassium may not be as crucial a nutrient as calcium or magnesium. The correlation between SDW and the K^+/ Mg^{2+} ratio (0.36**), as well as the concentrations of Ca (0.31**), Mg(0.29**), and K in the roots (0.12*), indicates that the K/Mg ratio and Ca levels in the roots are positively correlated with SDW and play a significant role in its growth. The correlation between SDW and the soil K^+/ Mg^{2+} ratio in the Zafar and Hyola50 cultivars was -0.36** and 0.36**, respectively. Based on the results of SDW and RDW, the Hyola50 cultivar showed a better response to increased levels of K in the soil. Therefore, a higher amount of K than Mg was required for optimal growth. In utilizing K, the Hyola50 cultivar is not as efficient as the other two cultivars. The results suggest that a stable amount of K^+/ Mg^{2+} in the soil cannot be recommended for all canola cultivars. In areas of Iran where both humid and dry, warm conditions are present and potentially used for cultivation, ensuring an adequate supply of K fertilizer is essential for the successful cultivation of the Hyola50 cultivar.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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