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ORIGINAL PAPER

Effect of multi-nutrient foliar fertilizers on the yield and quality of oilseed rape grown on different types of soil*

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Abstract

The main objective of this study was to compare the effectiveness of an innovative foliar multi-component fertilizer (PRO) with a fertilizer of standard formulation (TRA). TRA contained macronutrients (N, P, K), micronutrients (B, Cu, Fe, Mn, Mo, Zn, with Fe and Zn complexed with EDTA), and trace elements (Cr, I, Li, Se in mineral form). PRO had the same quantitative composition, but Fe and Zn were complexed with amino acids, and trace elements were combined with plant extracts. For PRO fertilizer, the effect of a two- and three-fold increase in application dose above the standard one was additionally studied. Experiments were carried out on oilseed rape cultivated in a vegetation hall on two different soil textures (loamy and sandy). The applied fertilizers significantly increased seed and straw yields of spring oilseed rape. The key determinant of yield was the soil type. Both fertilizers showed comparable effectiveness, although higher doses of PRO resulted in more pronounced yield increases. The beneficial effect of fertilization was observed on both soil types, with particularly strong plant responses noted on sandy soil. The concentration of certain macro- and microelements also increased after foliar fertilization. Among microelements, the highest percentage increases relative to unfertilized plants were recorded for iron in both seed and straw, and for manganese and copper in straw. The highest concentrations of microelements were recorded after applying higher doses of PRO. Of the trace elements, only lithium and selenium showed significant increases. In summary, the use of multi-nutrient foliar fertilizers represents an effective strategy for improving oilseed rape yield and quality, as well as a valuable tool for the biofortification of plants with essential nutrients.

Keywords: oilseed rape, foliar fertilization, mineral nutrients, biofortification, soil texture

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INTRODUCTION

In terms of cultivated area and production volume, oilseed rape (*Brassica napus* L.) is the second largest oilseed crop in the world, after soybeans, with global production reaching 91.9 million tonnes harvested from 43.4 million hectares in 2023 (FAOSTAT 2024). It is one of the most important sources of vegetable oil worldwide, while oilseed rape meal, a byproduct of oil extraction, is a key energy- and protein-rich raw material used in the production of livestock feed. The growing demand for food for both humans and animals, and the consequent need to increase production necessitate the search for and implementation of innovative solutions tailored to current needs. While the economic importance of spring oilseed rape in Poland is indeed marginal compared to winter varieties, this species serves as an excellent model for studying foliar fertilization strategies due to its shorter growing season and concentrated nutrient uptake period.

Modern agriculture faces numerous challenges arising from both adverse climate changes and the necessity to implement sustainable, environmentally friendly crop production practices. These constraints include the need to reduce intensive mineral fertilization and eliminate xenobiotics harmful to ecosystems. Climate change can lead to reduced crop yields, deterioration in product quality and, consequently, a decline in the profitability of agricultural production. To counteract these negative effects, both researchers and agricultural producers are actively seeking innovative fertilization technologies that are not only effective and economically viable but also environmentally safe. One promising solution is the use of multi-component fertilizers that supply plants not only with essential macro- and micronutrients (Cu, Fe, Mn, B, Mo, Zn) but also with trace elements such as Cr, I, Se, and Li (Khan et al. 2010, Jarecki et al. 2017, Januszkiewicz et al. 2023). These elements play a crucial role in human and animal nutrition, and their incorporation into fertilizers can contribute to the biofortification of crops, enhancing their nutritional value and positively impacting consumer health (Lima et al. 2018, Niewiadomska et al. 2020, Kiferle et al. 2021, Naeem et al. 2021, Ishfaq et al. 2023, Riyazuddin et al. 2023, Colak Esetlili et al. 2024). Numerous scientific studies also highlight the beneficial effects of these elements on plant growth, physiological processes, and enhanced tolerance to environmental stresses (Orlovius 2003, Nosenko et al. 2014, Shahzadi et al. 2015, Jankowski et al. 2019, Athar et al. 2020, Lupova et al. 2021, Cherkasova et al. 2024, Gholizadeh Sarcheshmeh et al. 2024).

Despite numerous initiatives, modern agriculture still primarily relies on low-efficiency soil fertilization, and its negative environmental impact is becoming an increasingly pressing issue. This applies both to the use of increasing doses of NPK fertilizers, with a low utilization rate (20-50%), which contributes to soil salinization and acidification, and to the fertilizer production process itself. Fertilizer manufacturing requires high energy inputs, generates significant greenhouse gas emissions, and leads to soil contamination with heavy metals in the vicinity of production facilities (Niu et al. 2021, Singh et al. 2024). To minimize this impact, it is essential to develop innovative and alternative fertilization methods with new fertilizer formulations (Herrera et al. 2016).

Foliar fertilization is becoming an increasingly central approach in crop nutrition technologies. This method allows for the effective supplementation of essential minerals in crops without excessively burdening the environment and can also enhance plant tolerance to adverse environmental conditions. However, the efficiency of foliar fertilization is influenced by multiple factors, including abiotic environmental parameters, plant physiology, and the chemical formulation of the applied minerals. Among abiotic environmental factors, soil properties play a crucial role in determining the effectiveness of foliar fertilization in terms of both yield quantity and quality. The results of our study on oilseed rape, along with findings from other researchers, have confirmed the significant importance of this factor (Stanislawska-Glubiak 2008, Chwil 2014, Xue et al. 2023). It is worth noting that more than 20% of arable land and 33% of irrigated land are degraded and salinized, which affects nutrient availability and their effectiveness in plant nutrition. On the other hand, many soils exhibit low levels of bioavailable micronutrients, which, combined with increasing crop yields, leads to their gradual depletion. As a result, the reduced micronutrient content in plants negatively affects their nutritional value for both feed and food purposes (White and Broadley 2009). According to Fernández and Eichert (2009) and Fernández and Brown (2013), the effectiveness of mineral fertilization is largely determined by the chemical form of the applied nutrients and their concentration. The chemical form affects the bioavailability of these elements, influencing their ability to penetrate leaf tissues, as well as their subsequent transport and utilization within the plant. Ongoing research aims to develop the most efficient foliar fertilizers. Innovative fertilizer formulations are being designed to enhance nutrient uptake by plants while minimizing losses and reducing environmental impact. One key direction of these studies is the development of nano-fertilizers, which utilize mineral activation techniques to generate reactive nanoparticles with improved absorption efficiency. Another important approach involves replacing synthetic metal-complexing agents, such as EDTA, with naturally occurring organic compounds, particularly amino acids. Additionally, these formulations may incorporate supplementary components that, on the one hand, improve the bioavailability of micronutrients and, on the other hand, act as biostimulants, enhancing crop yield potential.

We hypothesized that the innovative PRO fertilizer with amino acid-complexed micronutrients and plant extract-complexed trace elements would demonstrate superior effectiveness compared to the traditional TRA fertilizer, with differential responses depending on soil type, and that foliar fertilization would be particularly beneficial under challenging soil conditions (sandy soil) due to improved nutrient bioavailability.

The main objective of the study was to evaluate the effectiveness (including yield, yield quality and biofortification) of two multi-nutrient foliar fertilizers in oilseed rape cultivation on two different soil types (loamy and sandy). Each of the tested fertilizers contained macronutrients (N, P, K), micronutrients (B, Cu, Fe, Mn, Mo, and Zn), as well as trace nutrients (Cr, I, Li, and Se). The differences between the TRA and PRO fertilizers resulted from the use of different chemical forms of selected micronutrients and trace nutrients. The innovative PRO fertilizer contained iron and zinc (two of the most deficient elements in human and animal diets) chelated with amino acids, while the trace elements were chelated with plant extracts.

MATERIALS AND METHODS

Pot Experiment

A one-year pot experiment was carried out in 2023 in a vegetation hall of the Plant Nutrition Department of the Wroclaw University of Life Sciences. The research was conducted on spring oilseed rape of the Goliat variety characterized by high yield potential, high fat content, as well as good resistance to lodging and pod bursting (Hodowla Roślin Strzelce Grupa IHAR 2024).

Spring oilseed rape was selected as the model crop for this study due to its high nutritional requirements, particularly for micronutrients, and documented sensitivity to nutrient deficiencies that can significantly impact both yield and quality parameters. The vegetation period of the plants was 125 days, and the plants were harvested at full seed maturity. The experiment was set up in Wagner-type pots of 5 kg capacity. Each treatment was established in four replicates. During the growing season, soil moisture was controlled by watering with distilled water as needed, and maintained throughout the growing season at 50% of the field water capacity. Temperature and light conditions were natural. The experiment included 40 pots. Twenty pots (4 × control, 4 × TRA, 12 × PRO doses 1-3) were filled with loamy soil and the other twenty pots with sandy soil. Both soils were tested before setting up the experiment. Calcium was then added to ensure the correct pH, and other macronutrients were added to ensure optimal nutrient content appropriate for each soil type.

Soil type

Soil type was chosen as an experimental factor to investigate how different soil properties influence the effectiveness of foliar fertilization. The comparison of loamy and sandy soils enables the evaluation of the effectiveness of foliar fertilization across a wide range of soil fertility levels, which is particularly relevant for regions with diverse soil types.

Loamy soil. The pots were filled with soil collected from the humus horizon of a commercial field in Przeworno, Poland (50°68′N, 17°18′E), dominated by Haplic Luvisols (Episiltic, Endoloamic), characterized by silt loam texture (sand fraction 19%, silt 68%, loamy 13%), pH KCl of 5.2, and total content of organic carbon (C_{tot}) of 1.25%. The content of plant-available nutrients (measured using methods listed below) in the soil was as follows: phosphorus (P) 44 mg kg^{-1} (low content), potassium (K) 187 mg kg^{-1} (medium content), magnesium (Mg) 68 mg kg^{-1} (medium content), manganese (Mn) 171 mg kg^{-1} (medium content), iron (Fe) 1 754 mg kg^{-1} (medium content), copper (Cu) 5.9 mg kg^{-1} (medium content), and zinc (Zn) 9.9 mg kg^{-1} (low content).

Sandy soil. The pots were filled with soil collected from the humus horizon of a commercial field in Miloszyce, Poland (51°05′N, 17°31′E), dominated by Albic Luvisol (Epiarenic), characterized by sandy texture (sand fraction 90%, silt 7%, loamy 7%), soil pH KCl of 5.9, and C_{tot} of 0.95%. The content of plant-available nutrients in the soil was as follows: phosphorus (P) 98 mg kg^{-1} (high content), potassium (K) 105 mg kg^{-1} (high content), magnesium (Mg) 110 mg kg^{-1} (high content), manganese (Mn) 168 mg kg^{-1} (medium content), iron (Fe) 973 mg kg^{-1} (medium content), copper (Cu) 3.4 mg kg^{-1} (high content), and zinc (Zn) 13.6 mg kg^{-1} (high content).

Design of the Experiment

The composition and chemical forms of the components are presented in Table 1.

Table 1

Forms of nutrients in compound foliar fertilizers

Elements		Forms of Nutrients in Foliar Fertilisers	
		PRO	TRA
Macronutrients	N	Mineral form	Mineral form
	P	Mineral form	Mineral form
	K	Mineral form	Mineral form
Micronutrients	B	Mineral form	Mineral form
	Cu	EDTA chelate	EDTA chelate
	Fe	Amino acid complexed	EDTA chelate
	Mn	Manganese nitrate	Manganese nitrate
	Mo	Ammonium molybdate	Ammonium molybdate
	Zn	Amino acid complexed	EDTA chelate
Trace nutrients	Cr	Complexed with plant extracts	Mineral form
	I	Complexed with plant extracts	Mineral form
	Li	Complexed with plant extracts	Mineral form
	Se	Complexed with plant extracts	Mineral form

The experiment included five treatments: control (no fertilizer), treatment with reference fertilizer TRA (dose 1; 1.0%), and three doses of innovative fertiliser PRO (doses 1, 2, and 3; 1.0%, 2.0%, and 3.0%, respectively). The aim of using increasingly higher PRO fertiliser concentrations was aimed to assess the response of plants to more intensive fertilization and identify any toxic effects associated with the use of the formulation. During the growing season, foliar fertilizer treatments with TRA and PRO were scheduled at two plant developmental stages: the first application in the 8-10 leaf stage (BBCH 18-19) and the second in the green bud stage (BBCH 51).

Methods for Chemical Analysis

Representative soil and plant samples were collected for agricultural and chemical analysis. Soil pH was determined by the potentiometric method using 1 mol dm^{-3} KCl (CP505 digital pH-meter by Elemetron Co., Zabrze, Poland), the total C content was assessed with a C analyzer (Leco Co., Benton Harbor, MI, USA). The content of plant-available phosphorus and potassium was determined using the Egner and Riehm method (Egner et al. 1955), and the content of soluble magnesium was determined using the Schachtschabel method (Schachtschabel 1954). The contents of soluble micronutrients in the tested soils, such as Mn, Fe, Cu, and Zn, were determined by the Rinkis method (Rinkis and Растений 1972) using an AAS (Varian model SpectrAA 220FS).

The total content of nitrogen in the plant material collected during the study was determined using the Kjeldahl method. To determine the levels of other elements, the plant material was dry-mineralized, and then the ash was dissolved with nitric acid and amounts of the following elements were measured in the solution: phosphorus by a vanadate-molybdate method, potassium and calcium with flame photometry, and magnesium and microelements (Cu, Fe, Mn, and Zn) by atomic absorption spectrophotometry. The other elements, i.e. B, Cr, I, Li, Mo and Se, were determined by ICP-OES (Thermo Scientific iCAP 7400, Waltham, MA, USA). Iodine levels were below the detection threshold.

Statistical Analysis

The two-factor experiment was set up in a randomized design with four replicates. All results obtained were subjected to two- or one-way analysis of variance. The effect size was measured with generalized eta squared (η^2G), which quantifies the proportion of variance explained by each factor. Effect sizes were interpreted as follows (Olejnik and Algina 2003): values <0.01 indicate small, 0.01-0.06 medium, and >0.06 large effects. Before performing the analysis of variance, a test for the homogeneity of variance within groups was performed using the Levene's test and the Shapiro-Wilk test of the conformity of variables to normal distribution. The significance of differences between the means was assessed using the Tukey's post hoc test with a significance level of p<0.05. Regression Tree Analysis was performed using the rpart package in R (Therneau and Atkinson 2022), which enables recursive partitioning, and enables non-linear classification and prediction of the dependent variable through successive data segmentation. Model performance was assessed using root mean square error (RMSE) and coefficient of determination (R^2). For all statistical analyses, the statistical programme R 4.4.1 was used (R Core Team 2024).

RESULTS AND DISCUSSION

Plant Growth - Yield

Foliar fertilization exerted a significant effect on the seed and straw yields of oilseed rape, as illustrated in Figures 1-3.

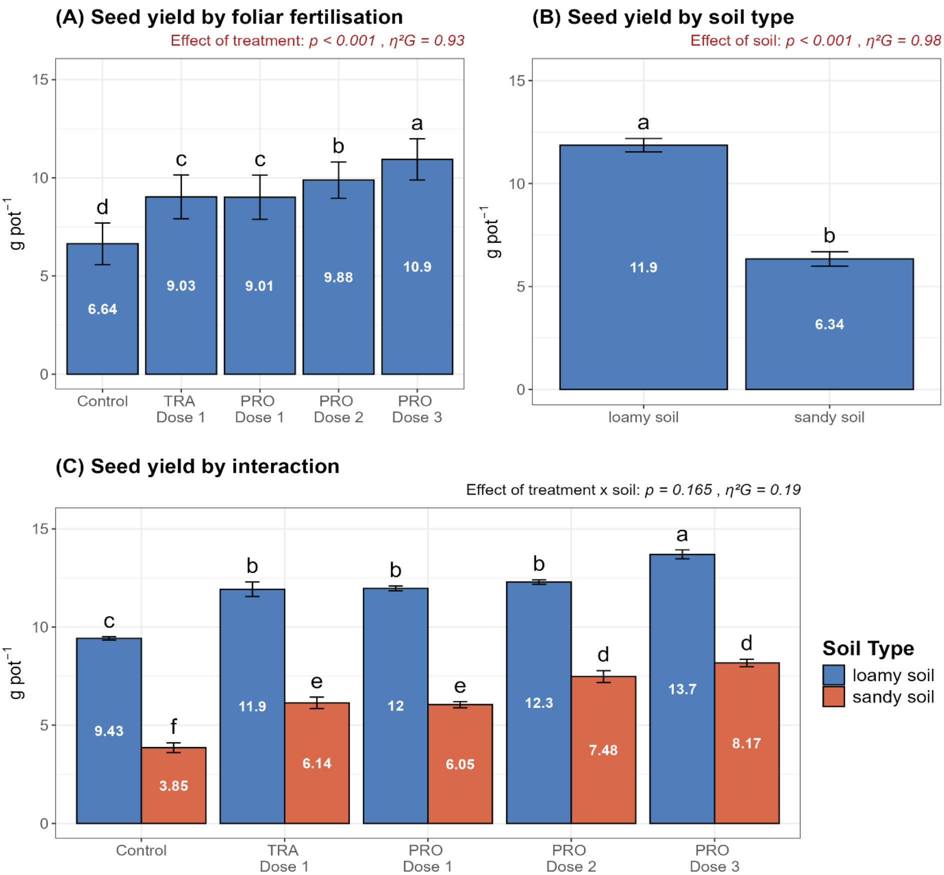

Fig. 1. Seed yield of spring oilseed rape

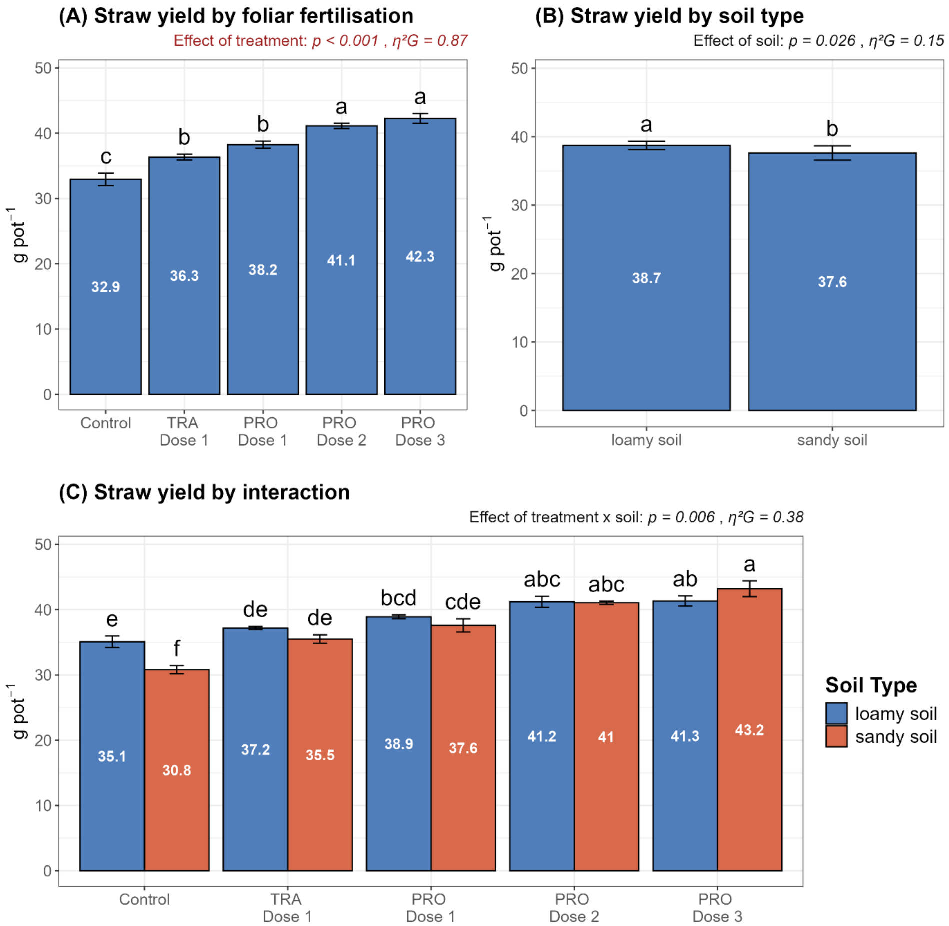

Fig. 2. Straw yield of spring oilseed rape

This is substantiated by η^2G values of 0.93, 0.87, and 0.91 for seed yield, straw yield, and total oilseed rape yield, respectively. The application of both TRA and PRO fertilizers resulted in comparable increases in seed yield, with an average improvement of 36% relative to unfertilized plants. Notably, higher doses of the PRO fertilizer proved to be more effective, leading to significantly greater yield enhancements. A similar trend was observed for straw dry matter and total yield, although the percentage increases in these parameters were lower than those recorded for seed yield. These results clearly show a positive impact of foliar fertilization on the main yield-forming component of oilseed rape, which is the seeds. A positive response of oilseed rape yield to foliar fertilization has also been demonstrated by other researchers (Yang Mei et al. 2009, Jakienė 2013, Sienkiewicz-Cholewa and Kieloch 2015, Jankowski, Hulanicki, Sokólski et al. 2016, Pużyńska et al.

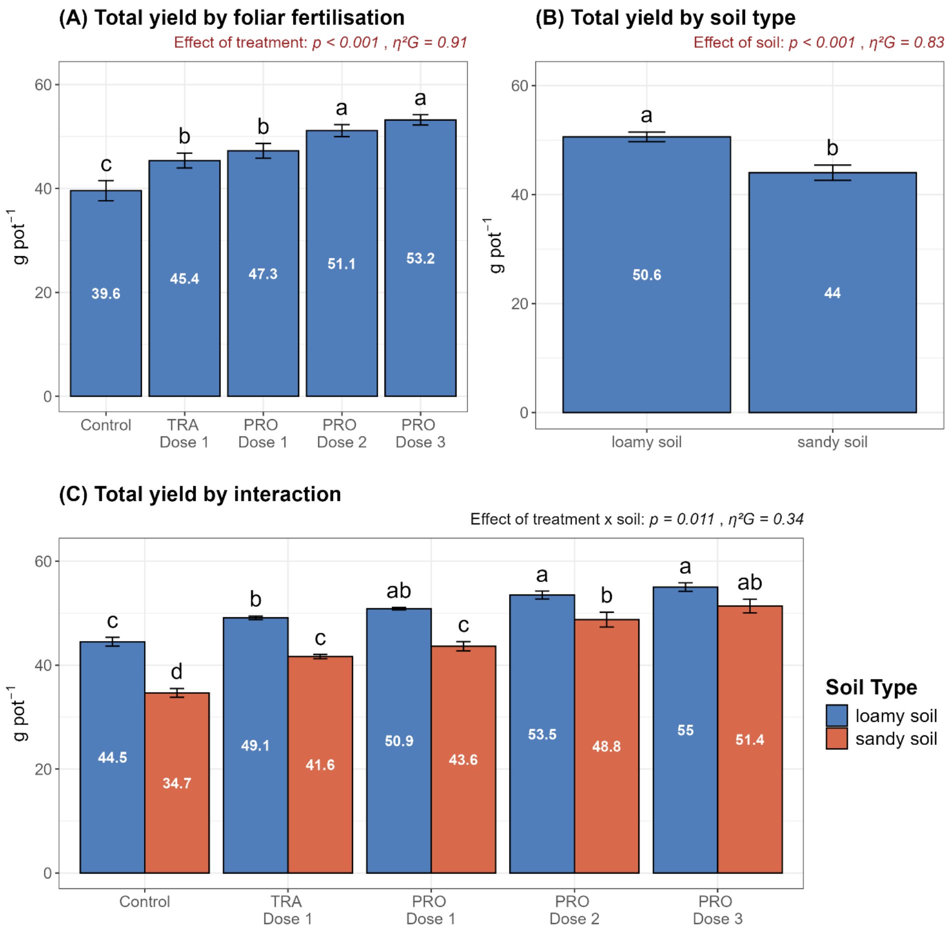

Fig. 3. Total yield (seed + straw) of spring oilseed rape

2018, Shahsavari 2019, Szczepanek et al. 2019, Rad et al. 2021). In addition, Jakienė (2013) demonstrated that the most effective formulation was a fertilizer enriched with macro- and micronutrients along with an amino acid complex, whose composition in terms of amino acids was comparable to that of the PRO complete fertilizer. It is worth noting that the increase in seed yield observed in our study was considerably higher than that reported in the cited literature. This may be attributed to the presence of trace elements in the applied formulation. Soil type also had a significant effect on oilseed rape yield, particularly on seed yield ($p < 0.001$, $\eta^2G = 0.98$). On loamy soil, the seed yield was nearly twice as high as on sandy soil. In the case of straw yield, the difference was considerably smaller, yet still statistically significant: 50.6 g pot^{-1} vs. 44.0 g pot^{-1}. Loamy soil promoted higher yields regardless of fertilization treatment, likely due to its superior water and nutrient retention capacity. The highest absolute seed yield was recorded for the PRO dose 3 treatment on loamy soil (13.7 g pot^{-1}). However, the greatest relative yield increase compared to the control (unfertilized plants) was observed on sandy soil, where PRO dose 3 enhanced seed yield by 112% (from 3.85 to 8.17 g pot^{-1}). This indicates that foliar fertilization may be particularly effective on soils with less favorable physical and chemical properties. Other researchers have also emphasized that the physicochemical parameters of soil are key environmental factors influencing the efficacy of foliar fertilization (Stanislawska-Glubiak 2008, Chwil 2014, Xue et al. 2023). The potential toxic effects of excessive doses of foliar fertilizers on plants should also be considered. In the conducted experiment, PRO fertilizer was applied in three different doses. The highest dose did not show a negative effect on plants. Following the application of the highest PRO dose (dose 3), the highest yields (seeds, straw, and total biomass) were recorded. However, there was no statistically significant difference between dose 2 and dose 3, suggesting that increasing the PRO dose beyond dose 2 may not provide additional benefits.

In summary, soil type was the dominant factor influencing rape yield, with significantly higher values observed in loamy soil compared to sandy soil. Fertilization treatments also significantly affected rape yield, with PRO dose 3 yielding the highest yield. Although foliar fertilization led to yield increases on both soils, the effects were more pronounced on the sandy soil, while the general trend remained consistent across both soil types.

Concentration of macronutrients

As shown in Tables 2 and 3, among the five macronutrients examined (nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca)), only the concentration of nitrogen in both seeds and straw remained relatively stable irrespective of foliar fertilization, with effect sizes (η^2G) of 0.37 and 0.38, respectively.

These results differ from our findings for triticale, which, in most cases, did not exhibit significant differences compared to untreated plants, indicating a different response of this species (Januszkiewicz et al. 2024). Both applied formulations (PRO and TRA) exhibited similar effects. However, only higher doses of PRO led to a statistically significant increase in the content of these macronutrients compared to TRA and PRO applied at the lower dose (1). The most pronounced positive effects (η^2G > 0.60) were observed for phosphorus content in seeds, potassium in seeds and straw, and magnesium in seeds. Compared to triticale (Januszkiewicz et al. 2024), oilseed rape seeds were particularly rich in nitrogen, phosphorus, magnesium, and calcium. As mentioned above, a strong plant response to foliar fertilization was observed for magnesium, potassium, and phosphorus. In light of the growing need to enhance nutrient use efficiency while simultaneously reducing soil fertilization with these macronutrients, foliar feeding is gaining particular

Table 2

Concentrations of nitrogen, phosphorus and potassium in spring oilseed rape

Effect	Nitrogen		Phosphorus		Potassium	
	Seeds	Straw	Seeds	Straw	Seeds	Straw
	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.
Treatment *(F1)*						
Control	36.3 b	9.75 ab	8.49 c	4.73 b	8.16 c	16.6 c
TRA dose 1	37.1 ab	8.72 b	8.90 b	5.43 ab	8.50 bc	19.5 ab
PRO dose 1	37.5 ab	10.4 ab	8.98 b	5.44 a	8.73 b	19.3 b
PRO dose 2	37.8 ab	11.3 a	9.15 ab	5.49 a	8.86 ab	20.0 ab
PRO dose 3	38.8 a	10.9 a	9.38 a	5.56 a	9.26 a	20.4 a
Soil *(F2)*						
loamy	40.5 a	9.37 b	8.61 b	6.36 a	8.98 a	29.1 a
sandy	34.4 b	11.0 a	9.34 a	4.30 b	8.42 b	9.14 b
Interaction: *(F1 x F2)*						
Control : loamy	39.6 a	9.59 ab	7.84 d	5.96 a	8.29 cd	26.8 b
TRA dose 1 : loamy	40.4 a	6.72 b	8.48 c	6.39 a	8.64 bcd	29.3 a
PRO dose 1 : loamy	40.0 a	9.44 ab	8.61 bc	6.41 a	8.93 bc	29 a
PRO dose 2 : loamy	41.0 a	11.0 a	8.91 abc	6.49 a	9.22 ab	30.2 a
PRO dose 3 : loamy	41.7 a	10.1 a	9.24 a	6.52 a	9.86 a	30.4 a
Control : sandy	33.0 b	9.9 ab	9.14 ab	3.49 b	8.02 d	6.31 d
TRA dose 1 : sandy	33.8 b	10.7 a	9.32 a	4.46 b	8.36 cd	9.61 c
PRO dose 1 : sandy	34.9 b	11.3 a	9.35 a	4.47 b	8.53 bcd	9.67 c
PRO dose 2 : sandy	34.5 b	11.5 a	9.39 a	4.49 b	8.5 bcd	9.82 c
PRO dose 3 : sandy	35.8 b	11.8 a	9.51 a	4.60 b	8.67 bcd	10.3 c
p-value F1	$p = 0.007$	$p = 0.005$	$p < 0.001$	$p = 0.012$	$p < 0.001$	$p < 0.001$
p-value F2	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
p-value F1xF2	$p = 0.717$	$p = 0.07$	$p = 0.005$	$p = 0.756$	$p = 0.028$	$p = 0.354$
Effect size (η^2G) - F1	*0.37*	*0.38*	*0.64*	*0.34*	*0.65*	*0.86*
Effect size (η^2G) - F2	*0.89*	*0.34*	*0.73*	*0.85*	*0.52*	*1.00*
Effect size (η^2G) - F1xF2	*0.07*	*0.24*	*0.38*	*0.06*	*0.30*	*0.13*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

Table 3

Concentrations of magnesium and calcium in spring oilseed rape

Effect	Magnesium		Calcium	
	Seeds	Straw	Seeds	Straw
	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.	g kg^{-1} d.m.
Treatment *(F1)*				
Control	4.55 d	2.95 b	4.73 b	7.65 b
TRA dose 1	4.83 c	3.51 a	4.92 ab	8.55 a
PRO dose 1	5.00 bc	3.5 a	4.92 ab	8.42 a
PRO dose 2	5.10 ab	3.52 a	5.01 a	8.46 a
PRO dose 3	5.25 a	3.36 ab	5.13 a	8.33 a
Soil *(F2)*				
loamy	4.48 b	2.26 b	5.47 a	7.83 b
sandy	5.42 a	4.47 a	4.41 b	8.74 a
Interaction: *(F1 x F2)*				
Control : loamy	4.21 f	2.19 c	5.24 b	7.54 d
TRA dose 1 : loamy	4.40 ef	2.28 c	5.43 ab	7.99 bcd
PRO dose 1 : loamy	4.50 def	2.28 c	5.42 ab	7.80 d
PRO dose 2 : loamy	4.56 de	2.31 c	5.54 ab	7.98 bcd
PRO dose 3 : loamy	4.72 cd	2.26 c	5.71 a	7.84 cd
Control : sandy	4.89 c	3.71 b	4.22 c	7.76 d
TRA dose 1 : sandy	5.27 b	4.74 a	4.40 c	9.11 a
PRO dose 1 : sandy	5.51 ab	4.72 a	4.42 c	9.03 a
PRO dose 2 : sandy	5.64 a	4.72 a	4.48 c	8.94 ab
PRO dose 3 : sandy	5.79 a	4.46 a	4.55 c	8.83 abc
p-value F1	$p < 0.001$	$p = 0.002$	$p = 0.003$	$p = 0.001$
p-value F2	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
p-value F1xF2	$p = 0.017$	$p = 0.015$	$p = 0.912$	$p = 0.164$
Effect size (η^2G) - F1	*0.82*	*0.42*	*0.40*	*0.44*
Effect size (η^2G) - F2	*0.95*	*0.95*	*0.92*	*0.60*
Effect size (η^2G) - F1xF2	*0.32*	*0.33*	*0.03*	*0.19*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

importance. Numerous researchers have indicated that foliar fertilization is an effective strategy to improve the uptake efficiency of these macronutrients (N, P, K, Mg), while also contributing to enhanced stress tolerance (Adnan et al. 2021, Görlach et al. 2021, Song et al. 2024, Zhao et al. 2025). The increases observed in our experiment may be attributed to the application of TRA and PRO fertilizers, which contain a set of macronutrients. However, given their relatively low content in relation to plant demand (intended to supplement and safeguard against potential deficiencies of key macronutrients during the early stages of plant growth and development), the positive response may result from synergistic mechanisms. As noted by Zheng (2018) and Ishfaq et al. (2023), foliar fertilization can stimulate the uptake of nutrients available in the soil. Furthermore, the beneficial effect may also stem from positive interactions among individual elements, leading to a mutual enhancement of their uptake (Bana *et al.* 2022).

In many cases, increasing the dose of PRO fertilizer contributed to a significant increase in the concentration of macronutrients in oilseed rape; however, the differences between doses 2 and 3 were not statistically significant, suggesting that PRO dose 2 is the optimal solution.

Due to intensive agricultural production and its planned further growth in the coming decades, the importance of phosphorus is becoming increasingly important as a non-renewable resource. One of the important characteristics of phosphorus is its low availability due to poor solubility and strong binding in the soil, which, in the near future, may be one of the main factors limiting the efficiency of crop production (Shen *et al.* 2011). Therefore, alternative and more efficient solutions are being sought. Bastani and Hajiboland (2017) showed that foliar phosphorus fertilization in oilseed rape is more effective than soil fertilization under phosphorus-deficient conditions, enhancing both yield parameters and phosphorus uptake. They also observed that foliar application prolongs root activity, improving soil phosphorus absorption - an important finding, given that plants typically utilize only 20-30% of soil-applied phosphorus (Syers et al. 2008). In our experiment, phosphorus concentration in seeds was significantly influenced by both foliar fertilization (F1, $p < 0.001$) and soil type (F2, $p < 0.001$), with moderate to large effect sizes (η^2G = 0.64–0.73). On loamy soil, foliar fertilization increased phosphorus concentration in seeds from 7.84 to 9.24 g kg^{-1}. On sandy soil, phosphorus concentration in seeds remained high regardless of treatment (9.14 - 9.51 g kg^{-1}, $p > 0.05$), indicating no significant response to fertilization. In straw, foliar fertilization (F1) also resulted in a slight increase in phosphorus concentration. Soil type (F2) was a major factor influencing phosphorus content, with higher levels observed in plants grown on loamy soil. Jankowski et al. (2016), investigating the effect of different rates of single- and multi-component foliar fertilizers, found that intensive foliar fertilization increased N, P, and K content in oilseed rape straw while reducing their concentrations in seeds. An opposite trend was observed for Mg and S, where higher fertilization intensity led to a decrease in their concentration in straw but an increase in seeds. In the case of Ca, the applied fertilization, regardless of the type of fertilizer and treatment, had no significant impact on its concentration. Our results indicate that foliar fertilization led to an increase in potassium content in both seeds and straw, with a more pronounced accumulation observed in the straw. This may be attributed to the crucial role of potassium in the osmoregulation of plant cells, which is particularly important throughout the entire growing season. Contrary to the findings of Jankowski, Hulanicki, Krzebietke, et al. (2016) regarding calcium, our experiment demonstrated a positive effect of foliar fertilization on calcium content, particularly in oilseed rape straw. However, all fertilization treatments applied resulted in a similar level of increase. This result is consistent with the findings reported by Stepaniuk and Głowacka (2021), who showed that doubling or tripling the fertilizer dose, regardless of the application method (foliar, soil, or combined), did not lead to significant increases in oilseed rape yield.

A number of studies have shown that foliar fertilization maintains or even increases yields while improving nutrient use efficiency, reducing fertilizer inputs and lowering environmental and production costs (Herrera et al. 2016, Pruszyński 2020, Ferrari et al. 2025). Studies also confirm that foliar application promotes better root and shoot development, enhances yield quality parameters such as protein and oil content, and increases the accumulation of macronutrients in plant tissues (Wang et al. 2012, Żarczyński et al. 2021, Ramakrishna et al. 2022). These benefits are further amplified by the possibility of combining foliar fertilization with plant protection treatments, reducing the number of field operations and minimizing soil compaction.

In summary, as in the case of seed yield, straw yield and total yield, soil type was an important determinant of macronutrient concentrations in aerial parts of oilseed rape. Soil type was statistically significant for all analyzed elements ($p < 0.001$). Oilseed rape seeds grown on loamy soil showed significantly higher concentrations of three macronutrients: N, K and Ca, compared to seeds grown on a sandy soil. In contrast, oilseed rape straw grown on loamy soil had higher concentrations of phosphorus and potassium.

Concentration of micronutrients

In addition to macronutrients (N, P, K), the tested multi-nutrient formulations contained a range of essential micronutrients such as B, Cu, Fe, Mn, Mo and Zn, as well as trace elements including chromium, iodine, lithium, and selenium. In the PRO formulation, an innovative technology was applied that combines Zn and Fe with amino acids, while trace elements were complexed with plant extracts. In the context of biofortification, the concentrations of these elements were subsequently determined in the seeds and straw of oilseed rape. Generally, a statistically highly significant effect ($p < 0.001$) of foliar fertilization (F1) and soil type (F2) on the concentration of micronutrients in both seeds and straw was observed. The effect size (η^2G) for both factors was high to very high, ranging from 0.54 to 1.00. An exception was found for molybdenum concentration in straw, where the effect of fertilization was not significant (p = 0.155) and the effect size was low (η^2G = 0.19). As a result of foliar fertilization, the concentrations of all analyzed micronutrients in oilseed rape seeds increased (Tables 4 and 5).

Table 4

Concentrations of manganese, iron and copper in spring oilseed rape

Effect	Manganese		Iron		Copper	
	Seeds	Straw	Seeds	Straw	Seeds	Straw
	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.
Treatment *(F1)*						
Control	43.6 d	35.4 c	69.7 c	36.5 c	5.44 c	3.56 c
TRA dose 1	45.7 c	53.5 b	88.4 b	61.7 b	5.65 bc	4.15 b
PRO dose 1	47.4 b	56.8 ab	88.8 b	63.4 b	5.70 ab	4.16 b
PRO dose 2	48.2 ab	58.7 a	92.1 a	71.2 a	5.82 ab	4.82 a
PRO dose 3	49.3 a	60.7 a	93.1 a	72.9 a	5.91 a	4.85 a
Soil *(F2)*						
loamy	55.8 a	67.6 a	117 a	89.8 a	5.12 b	4.44 a
sandy	37.9 b	38.5 b	55.7 b	32.5 b	6.29 a	4.18 b
Interaction: *(F1 x F2)*						
Control : loamy	51.5 c	41.0 bc	83.4 c	45.2 c	4.74 c	3.74 de
TRA dose 1 : loamy	53.5 c	72.2 a	120 b	93.6 b	5.06 bc	4.2 bcd
PRO dose 1 : loamy	56.6 b	73.9 a	120 b	93.5 b	5.12 bc	4.28 abcd
PRO dose 2 : loamy	57.9 ab	74.7 a	129 a	107 a	5.3 b	5.01 a
PRO dose 3 : loamy	59.4 a	76.2 a	133 a	110 a	5.39 b	4.95 ab
Control : sandy	35.6 e	29.8 d	55.9 d	27.8 e	6.13 a	3.38 e
TRA dose 1 : sandy	37.8 d	34.8 cd	57.1 d	29.8 de	6.24 a	4.09 cde
PRO dose 1 : sandy	38.1 d	39.8 bc	57.2 d	33.2 de	6.28 a	4.04 cde
PRO dose 2 : sandy	38.6 d	42.8 b	54.9 d	35.5 d	6.34 a	4.63 abc
PRO dose 3 : sandy	39.2 d	45.2 b	53.5 d	36.2 d	6.43 a	4.74 abc
p-value F1	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
p-value F2	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.019$
p-value F1xF2	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.292$	$p = 0.922$
Effect size (η^2G) - F1	*0.88*	*0.92*	*0.97*	*0.96*	*0.54*	*0.74*
Effect size (η^2G) - F2	*0.99*	*0.96*	*1.0*	*0.99*	*0.94*	*0.17*
Effect size (η^2G) - F1xF2	*0.62*	*0.73*	*0.98*	*0.93*	*0.15*	*0.03*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

Table 5

Concentrations of zinc, boron and molybdenum in spring oilseed rape

Effect	Zinc		Boron		Molybdenum
	Seeds	Straw	Seeds	Straw	Straw
	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.
Treatment *(F1)*					
Control	61.7 c	39.2 c	10.0 b	31.0 b	1.39 a
TRA dose 1	63.8 bc	43.7 b	10.9 a	36.8 a	1.50 a
PRO dose 1	63.9 bc	45.8 ab	11.2 a	36.9 a	1.49 a
PRO dose 2	65.1 b	49.0 a	11.3 a	37.3 a	1.55 a
PRO dose 3	69.6 a	47.2 ab	11.4 a	38.0 a	1.59 a
Soil *(F2)*					
loamy	72.3 a	45.6 a	13.5 a	50.7 a	2.370 a
sandy	57.3 b	44.3 a	8.43 b	21.3 b	0.636 b
Interaction: *(F1 x F2)*					
Control : loamy	64.5 c	38.7 c	11.8 b	43.8 b	2.20 a
TRA dose 1 : loamy	70.1 b	42.9 bc	13.3 a	52.4 a	2.35 a
PRO dose 1 : loamy	71.8 b	44.2 abc	14.0 a	52.2 a	2.32 a
PRO dose 2 : loamy	73.7 b	51.1 a	14.2 a	52.4 a	2.46 a
PRO dose 3 : loamy	81.4 a	51.3 a	14.3 a	53.0 a	2.53 a
Control : sandy	58.9 d	39.6 c	8.22 c	18.3 d	0.585 b
TRA dose 1 : sandy	57.5 d	44.6 abc	8.41 c	21.1 cd	0.64 b
PRO dose 1 : sandy	56 d	47.4 ab	8.39 c	21.7 c	0.667 b
PRO dose 2 : sandy	56.5 d	47 ab	8.51 c	22.3 c	0.639 b
PRO dose 3 : sandy	57.8 d	43 bc	8.60 c	23.0 c	0.648 b
p-value F1	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.155$
p-value F2	$p < 0.001$	$p = 0.166$	$p < 0.001$	$p < 0.001$	$p < 0.001$
p-value F1xF2	$p < 0.001$	$p = 0.003$	$p = 0.002$	$p = 0.001$	$p = 0.407$
Effect size (η^2G) - F1	*0.77*	*0.63*	*0.55*	*0.83*	*0.19*
Effect size (η^2G) - F2	*0.96*	*0.06*	*0.97*	*0.99*	*0.98*
Effect size (η^2G) - F1xF2	*0.81*	*0.41*	*0.42*	*0.44*	*0.12*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

Compared to the control, the application of TRA and the lowest dose of PRO resulted in similar increases in micronutrient concentrations, ranging from 4% to 50%, with the highest increase observed for molybdenum in rapeseed on loamy soil (Table 6). On sandy soil, molybdenum content was below the detection limit.

Table 6

Molybdenum concentration on loamy soil

Effect	Molybdenum	
	Seeds	Straw
	mg kg^{-1} d.m.	mg kg^{-1} d.m.
Loamy soil		
Control	0.417 c	2.09 c
TRA dose 1	0.568 b	2.35 abc
PRO dose 1	0.628 ab	2.32 bc
PRO dose 2	0.651 a	2.54 ab
PRO dose 3	0.671 a	2.68 a
p-value	*$p < 0.001$*	*$p < 0.001$*
Effect size (η^2G)	*0.92*	*0.69*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

Substantially greater increases (9% – 61%) were achieved only with higher doses of PRO. In the straw, the relative increases were much more pronounced, following the application of TRA and the lowest PRO dose, micronutrient concentrations rose by 11% – 69%. An exception was molybdenum, for which no statistically significant increase was detected. The greatest increase in the straw concerned iron, a key micronutrient from the perspective of human and animal nutrition. The application of the medium and high PRO doses resulted in a twofold increase in iron concentration in straw, with no significant difference between these two doses. A similar trend was observed for copper. A lack of difference between PRO doses 2 and 3 was also observed for some other micronutrients. This is consistent with the results obtained for macronutrients where it was demonstrated that the optimal solution is the application of dose 2 of the PRO fertilizer.

In the conducted experiment, soil type also had a significant effect on the concentrations of micronutrients. Higher values of Mn, Fe, Zn, B and Mo were observed in oilseed rape grown on loamy soil, while sandy soil favored the accumulation of Cu. However, it is worth noting that the loamy soil contained higher amounts of iron and copper than the sandy soil. The soil effect was statistically significant for all micronutrients present in the seeds ($p < 0.001$). No significant differences were observed in Zn and Mo content in the oilseed rape straw ($p = 0.166$ and $p = 0.203$, respectively).

In most cases (Mn, Fe, Zn, and B, $p < 0.05$), a significant interaction was observed between foliar fertilization and soil type, indicating that the effectiveness of the treatment depends on soil conditions. Only for copper was the fertilization effect similar across both soil types, as evidenced by the lack of a significant interaction – from $p = 0.292$ for Cu in seeds to $p = 0.922$ for Cu in straw.

Overall, the application of the PRO fertilizer, particularly at the highest dose, resulted in statistically significant increases in micronutrient concentrations in oilseed rape. Other researchers have also shown a positive effect of intensive foliar fertilization on micronutrient content in oilseed rape (Jankowski, Hulanicki, Krzebietke, et al. 2016, Shahsavari 2019, Rad et al. 2021). Particular emphasis is placed on enrichment of crop plants with zinc. On the one hand, this is due to the need to eliminate the phenomenon of so-called hidden starvation (low zinc content in plant products), and on the other hand to optimally supply plants with this element. It is important for the proper course of biochemical and physiological processes in plants and the response of plants to environmental stresses (Noulas et al. 2018).

Concentration of trace elements

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

For chromium (Table 7), foliar fertilization (F1) had no significant effect on Cr concentration in seeds ($p = 0.369$), whereas a highly significant effect was observed for Cr concentration in straw ($p < 0.001$). All fertilization variants (TRA and PRO at doses 1, 2, and 3) resulted in a comparable increase of approximately 40% in chromium concentration in straw relative to the control.

Soil type (F_2) significantly influenced chromium concentration in seeds ($p < 0.001$) but had no significant effect on chromium concentration in straw ($p = 0.203$). Plants grown on sandy soil accumulated higher amounts of chromium and exhibited similar concentrations of this element in both seeds and straw. No significant interaction (F1 × F2) was found for chromium concentration in seeds and straw.

In the case of lithium, both foliar fertilization (F1) and soil type (F2) significantly influenced the concentration of Li in straw ($p < 0.001$). The concentrations of Li in straw was markedly higher following foliar fertilization, particularly with higher PRO doses. The interaction between fertilization and soil type (F1× F2) was also significant for lithium ($p < 0.001$), indicating that the effect of fertilization varied depending on the soil. PRO fertilization, especially at increased doses, had a stronger effect compared to TRA on lithium accumulation. The lithium concentration in the rapeseed was below the detection limit.

Selenium was determined in seeds and straw only on loamy soil. On sandy soil, Se concentration was below the detection limit. Foliar fertilization had a significant effect on Se concentration in seeds ($p = 0.003$) and straw ($p < 0.001$). There were no differences between the effects of TRA and PRO fertilizer at dose 1, while the highest dose of PRO (dose 3) resulted in a 25%

Table 7

Concentrations of chromium and lithium in spring oilseed rape

Effect	Chromium		Lithium	
	Seeds	Straw	Seeds	Straw
	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.	mg kg^{-1} d.m.
Treatment *(F1)*				
Control	0.792 a	0.766 b	BDL[1]	0.617 c
TRA dose 1	0.877 a	1.00 a	BDL[1]	1.23 b
PRO dose 1	0.826 a	1.07 a	BDL[1]	1.12 b
PRO dose 2	0.854 a	1.06 a	BDL[1]	2.07 a
PRO dose 3	0.891 a	1.08 a	BDL[1]	2.22 a
Soil *(F2)*				
loamy	0.717 b	1.01 a	BDL[1]	2.03 a
sandy	0.979 a	0.981 a	BDL[1]	0.868 b
Interaction: *(F1 x F2)*				
Control : loamy	0.656 c	0.802 b	BDL[1]	0.737 de
TRA dose 1 : loamy	0.711 bc	0.981 a	BDL[1]	1.8 b
PRO dose 1 : loamy	0.708 bc	1.11 a	BDL[1]	1.4 bc
PRO dose 2 : loamy	0.753 bc	1.07 a	BDL[1]	3.07 a
PRO dose 3 : loamy	0.756 bc	1.09 a	BDL[1]	3.15 a
Control : sandy	0.928 ab	0.73 b	BDL[1]	0.496 e
TRA dose 1 : sandy	1.04 a	1.02 a	BDL[1]	0.649 de
PRO dose 1 : sandy	0.945 ab	1.03 a	BDL[1]	0.831 de
PRO dose 2 : sandy	0.955 ab	1.06 a	BDL[1]	1.07 cd
PRO dose 3 : sandy	1.02 a	1.07 a	BDL[1]	1.29 c
p-value F1	$p = 0.369$	$p < 0.001$	*BDL*[1]	$p < 0.001$
p-value F2	$p < 0.001$	$p = 0.203$	*BDL*[1]	$p < 0.001$
p-value F1xF2	$p = 0.805$	$p = 0.418$	*BDL*[1]	$p < 0.001$
Effect size (η^2G) - F1	*0.13*	*0.79*	*BDL*[1]	*0.94*
Effect size (η^2G) - F2	*0.67*	*0.05*	*BDL*[1]	*0.93*
Effect size (η^2G) - F1xF2	*0.05*	*0.12*	*BDL*[1]	*0.83*

[1] BDL – Below Detection Limit

increase in content in seeds and 87% in straw compared to the control (table 8).These findings indicate that the efficiency of foliar fertilization is strongly dependent on both the type of plant tissue and soil conditions, and that applying higher fertilizer doses may be necessary to achieve detectable improvements.

Table 8

Selenium concentration on loamy soil

Effect	Selenium	
	Seeds	Straw
	mg kg^{-1} d.m.	mg kg^{-1} d.m.
Loamy soil		
Control	0.708 b	0.0532 c
TRA dose 1	0.789 ab	0.0698 bc
PRO dose 1	0.808 ab	0.0678 bc
PRO dose 2	0.847 a	0.080 ab
PRO dose 3	0.882 a	0.0995 a
p-value	$p = 0.003$	$p < 0.001$
Effect size (η^2G)	*0.64*	*0.79*

Means followed by the same letter do not differ significantly ($p > 0.05$, Tukey's HSD test)

The results of our study, in line with findings reported by other authors, indicate that foliar application of selected metals such as chromium and lithium, as well as other essential elements like selenium, may serve as an effective strategy for plant biofortification, providing a sustainable alternative to conventional soil fertilization. This approach helps to minimize the risk of excessive heavy metal accumulation in soils, which could otherwise lead to environmental contamination. Allah Ditta et al. (2021) emphasize that elevated concentrations of certain metals, such as chromium, in the soil can pose a serious environmental problem. Both chromium, lithium, and other metals, when present at high concentrations, can disrupt normal cellular functions. A significant body of research is currently focused on understanding these adverse effects and developing strategies to mitigate them (Zaheer et al. 2020, Razzaq et al. 2024, Iftikhar et al. 2025).

Recent studies have highlighted the beneficial effects of foliar lithium application on plants, including enhanced photosynthetic efficiency and water use (dos Santos et al. 2019, Buendía-Valverde et al. 2024, Ramos et al. 2025). dos Santos et al. (2019) showed that lithium's chemical form affects its efficacy, with LiOH being more effective than Li_2SO_4. Foliar application, regardless of the form, also increased nitrogen, phosphorus and potassium levels in plant tissues. Safe application limits were determined at 46.8 mg kg^{-1} for LiOH and 91.5 mg kg^{-1} for Li_2SO_4. Exceeding these thresholds may trigger oxidative stress, which disrupts key biochemical processes and ultimately leads to inhibited plant growth. In the present study, no adverse effects associated with the applied doses of lithium or chromium were observed.

In the tested foliar fertilizer, selenium and iodine were also present. In recent years, the use of selenium in fertilizers has become increasingly widespread ((Liu et al. 2017, Davoudi et al. 2019, Praus et al. 2019). However, it should be remembered that the use of excessively high doses may contribute to significant decreases in yields (Xu and Li 2023) and its effectiveness may depend on soil parameters (Száková et al. 2017).

This trend is primarily driven by the recognition that selenium is an essential micronutrient for human and animal nutrition. While selenium is not classified as an essential element for plants, it is regarded as a beneficial element, meaning that it has the potential to positively influence plant growth and development. Its application in agriculture is associated with various advantageous effects, including improved plant vigor, enhanced stress tolerance, and, in some cases, increased crop quality and yield (Nawaz et al. 2015, Yuan et al. 2023). The presence of both selenium and iodine in the tested formulation highlights a growing interest in the fortification of crops not only for agronomic benefits, but also to enhance the nutritional value of plant-derived food products. Unfortunately, the iodine concentration in the analyzed tissues was too low to be detected. Selenium, on the other hand, was found exclusively in the seeds and straw of oilseed rape cultivated on loamy soil. In this instance, foliar fertilization demonstrated a clear and significant influence on selenium accumulation. The effect of increasing doses of selenium on its accumulation in different plants was studied by Borowska and Koper (2011). They showed that increasing doses of the element lead to an increase in selenium content only up to a certain species-specific level, followed by a decrease in accumulation. Conversely, Goharian et al. (2021) reported that the application of selenium alone in oilseed rape cultivation was less effective compared to its combined application with other elements, such as zinc. The authors emphasized that this nutrient combination was particularly effective in mitigating losses associated with delayed sowing and abiotic stress conditions. In studies on foliar fertilization and biofortification, researchers highlight the importance of selecting appropriate elements and adjusting their concentrations so as not to compromise crop yield. They also underline the importance of considering potential interactions between nutrients, particularly antagonistic ones, that may impact nutrient uptake and plant productivity (Medrano-Macías et al. 2016, Száková et al. 2017, Golob et al. 2020).

Taken together, current findings highlight that the successful implementation of biofortification strategies requires careful adaptation to local environmental conditions, including soil properties, climate, and existing nutrient availability.

Nutrient interactions and their effects on oilseed rape yield depending on soil type

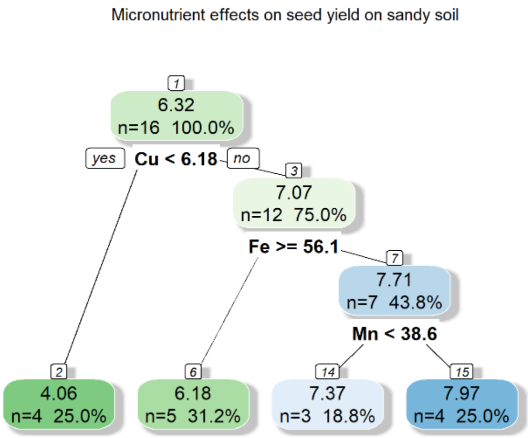

Fig. 4 Analysis of the decision tree for seed yield on sandy soil

The regression tree analysis reveals the hierarchical influence of micronutrients on oilseed rape seed yield in sandy soil conditions (Fig. 4). Cu concentration emerges as the primary determining factor, with a threshold value of 6.18 mg kg^{-1} dividing the dataset into two distinct pathways. Samples with Cu concentrations below this threshold (Cu < 6.18) show substantially lower seed yields (4.06 g pot^{-1}), representing 25% of the observations. For plants with higher Cu concentrations (≥ 6.18), Fe content becomes the next significant factor with a threshold of 56.1 mg kg^{-1}. Within this higher Cu group, Mn further refines the prediction model with a threshold

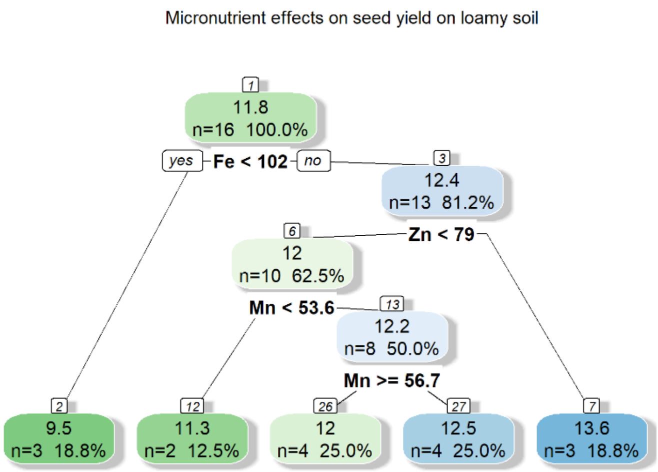

Fig. 5 Analysis of the decision tree for seed yield on loamy soil

of 38.6 mg kg^{-1}. The highest yield (7.97 g pot^{-1}) is observed when Cu ≥ 6.18, Fe ≥ 56.1, and Mn ≥ 38.6. The model demonstrates modest predictive performance with RMSE of 1.737 and R^2 of 0.040, suggesting that while micronutrients explain some yield variation, other factors likely contribute to yield differences in sandy soil conditions.

Fig. 5 shows regression tree analysis of a hierarchical effect of micronutrients on oilseed rape seed yield under loamy soil conditions. Fe concentration emerges as the main discriminating factor, with a threshold value of 102 mg kg^{-1}. Samples with Fe concentrations below this threshold show significantly lower seed yields (9.5 g pot^{-1}), accounting for 18.8% of observations. For plants with higher Fe concentrations (≥ 102), Zn content becomes another important factor with a threshold of 79 mg kg^{-1}. When Zn exceeds this threshold, the highest yield is achieved (13.6 g pot^{-1}). In the group with lower Zn content, Mn further refines the predictive model with intermediate thresholds of 53.6 and 56.7 mg kg^{-1}, resulting in varying yields between 11.3 and 12.5 g pot^{-1}. The model shows strong predictive performance with an RMSE of 0.449 and an R^2 of 0.952, suggesting that micronutrient concentrations are effective in explaining yield variation under loamy soil conditions, with particularly high statistical reliability.

CONCLUSIONS

Multi-nutrient foliar fertilizers (PRO and TRA) significantly enhanced spring oilseed rape yield and quality, with both formulations showing comparable effectiveness. Higher PRO doses produced greater improvements, particularly on sandy soil, demonstrating the potential of foliar fertilization under challenging soil conditions. Foliar application increased macronutrient concentrations (K, P, Mg) and substantially enhanced micronutrient content, especially iron, manganese, and copper. Trace element biofortification was achieved for lithium and selenium. No phytotoxic effects occurred at maximum doses tested. These results confirm foliar multi-nutrient fertilization as an effective, safe strategy for improving crop productivity and nutritional quality, with particular benefits under suboptimal soil conditions.

Author contributions

R.J. – conceptualization, investigation, methodology, data curation, visualization, project administration, writing – original draft preparation, writing – review & editing, G.K. – methodology, data care, visualization, supervision, writing – review & editing, E.S. – validation, visualization writing – original version, writing – review & editing. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflict of interest. 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. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. The authors received no specific funding for this work.

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