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ORIGINAL PAPER

Response of winter wheat to foliar fertilization with microelements*

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Abstract

Foliar fertilization with micronutrients is an important element of winter wheat cultivation, especially in combination with intensive agricultural practices. Micronutrients improve macronutrient utilization, plant health, and yield volume and quality. A field experiment with winter wheat of the RGT Kilimanjaro variety was carried out in the seasons 2021/2022 and 2023/2024 at the University of Rzeszów Experimental Station in Krasne, near Rzeszów. The aim of the study was to investigate the effect of winter wheat foliar fertilization with micronutrients, i.e. zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo) and boron (B), as compared to the control treatment. A one-factor experiment was established on a brown soil, quality class IIIa, good wheat complex. The levels of absorbable macronutrients (P, K, Mg) in the soil were high, while the levels of micronutrients (Fe, Zn, Mn, Cu, B) were found to be medium. The weather conditions during the plant vegetation period varied over the years of the research, which modified the effects of foliar fertilization. The difference in grain yield between 2022 and 2023 was 1.4 t ha^{-1}. The SPAD (soil plant analysis development) measurement showed that foliar fertilization with Cu and Mn was the most effective treatment, increasing the grain yield by 0.19 t ha^{-1} and 0.15 t ha^{-1}, respectively, compared to the control treatment. This was the result of an increase in the grains number per spike (GNS) and the thousand grain weight (TGW) after spraying with these microelements. Grain protein content (GPC) increased significantly after the application of Cu, Mo, Mn and Zn. Foliar fertilization differentiated the grain macronutrient and micronutrient values, but not always favorably, which resulted from synergism or antagonism between individual elements.

Keywords: *Triticum aestivum* L., nutrients, foliar fertilization, plant nutritional status, yield

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INTRODUCTION

Sustainable fertilization of cereals is necessary for securing high yields while maintaining good technological quality of the grain. Scientific literature mainly focuses on macronutrient fertilization, with particular emphasis on nitrogen (Gul et al. 2011, Stepien et al. 2019, Marcińska-Mazur, Mierzwa-Hersztek 2023). Nitrogen is the most important nutrient and should be supplied to plants optimally to prevent its loss in the soil profile (Paunescu et al. 2023, Jagiełło 2025). The demand of cereals for other macronutrients is also high and therefore such elements are applied to the soil with supplementary foliar application. In this context, Grzebisz et al. (2024) assert that the availability of nutrients in the soil should be high because it is the main source of nutrients for plants.

The response of individual cereal species to foliar fertilization is highly varied and depends on many factors (Vasundhara and Chhabra 2021, Ram et al. 2024). These especially include habitat conditions, but also genetic determinants or applied agrotechnical treatments (Stepien et al. 2019, Nowak, Wnuczek 2024). It should be emphasized that soil fertilization is a common and effective treatment, while foliar spraying is justified in high-yielding varieties and when other agrotechnical treatments have already been properly performed.

Foliar fertilization enables quick and easy penetration of nutrients through the leaves, which usually results in an increase in the volume and quality of the yield (Sobolewska et al. 2020, Vasundhara, Chhabra 2021, Ahmad et al. 2024). Jaskulska and Jaskulski (2019) showed that foliar application of nutrients increased yield components, yield size and grain protein content in wheat. Khan et al. (2009) also obtained an increase in grain yield after foliar spraying; however, an excessively high concentration of urea was toxic to plants. Sultonov et al. (2025) conclude that moderate soil fertilization with additional foliar fertilization is the best solution as it reduces environmental risks. Additionally, foliar fertilizers can be used together with pesticides, which reduces the number of spraying runs. In the study by Matras et al. (2022), such combined agrochemical treatments resulted in improved chlorophyll content in leaves (SPAD) and a reduction in fungal diseases. Szczepaniak et al. (2022) also demonstrated that the foliar application of micronutrients boosts the effects of wheat fungicide protection, especially at high nitrogen doses. However, other studies (Cwalina-Ambroziak et al. 2015, 2021) show that the impact of applied micronutrients on the degree of plant infestation by diseases is not always unambiguous.

Regarding the discussed aspect, Korzeniowska (2008) reported that with the same B content in the soil, only 4 out of 10 examined varieties responded with an increase in grain yield (8.6-15.2%) following foliar application of this microelement. Ralcewicz et al. (2009) and Chwil (2014) proved that wheat yields and wheat grain quality are primarily influenced by soil fertilization, while foliar fertilization should be treated as supplementary. Following the application of foliar fertilization, Bărdaş et al. (2023) obtained an improvement in the assimilation of plants and an average increase in yield from 450 to 765 kg ha^{-1}. They additionally showed an increase in grain protein and gluten content, and in the Zeleny index. Stepien et al. (2019) proved that foliar application of Mn contributed to an increase in the Zn and Fe content in wheat grain. On the other hand, they recorded negative correlations between the content of Cu and Mn, as well as Zn and Fe.

In conclusion, foliar fertilization is an effective agrotechnical practice, increasing the availability of nutrients and the efficiency of their uptake, and consequently improving grain yield and quality. The foliar application of micronutrients aiming to reduce their deficiencies in food is particularly important (İslamzade et al. 2025). Therefore, research in this field should be continued in various agro-environmental conditions.

The aim of the research was to determine the impact of foliar applications with micronutrients (Zn, Fe, Cu, Mn, Mo, B) on yield components, the SPAD index, yield volume, and chemical composition of grain of the RGT Kilimanjaro variety of winter wheat. The research hypothesis assumes that each of the individually applied micronutrients, particularly micronutrients (Zn, Fe, Cu, Mn, Mo, B), will increase yield and nutrient content in the grain.

MATERIALS AND METHODS

A field experiment with winter wheat was carried out in the seasons 2021/2022, 2022/2023 and 2023/2024 at the University of Rzeszów Experimental Station in Krasne near Rzeszów. A single-factor experiment was conducted in a randomized block design with four replications. The tested factor was foliar fertilization of the RGT Kilimanjaro variety of winter wheat with selected micronutrients. This is one of the most high-yielding varieties of winter wheat, belonging to quality group A. This variety is recommended for cultivation in the research area.

The fertilization variants were as follows: control (water spray), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), boron (B), zinc (Zn).

Foliar fertilizers were purchased from Intermag sp. z o.o., Olkusz, Poland. The applied fertilizers contained one main micronutrient:

– MIKROVIT® iron – 75 g L^{-1} Fe,
– MIKROVIT® copper – 75 g L^{-1} Cu,
– MIKROVIT® manganese – 160 g L^{-1} Mn,
– MIKROVIT® molybdenum – 33 g L^{-1} Mo,
– BORMAX® boron – 150 g L^{-1} B,
– MIKROVIT® zinc – 112 g L^{-1} Zn.

The plant development stages are given according to the BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale. Foliar fertilization was performed twice with a manual sprayer (Kwazar Orion 9L) in the 6 leaves unfolded stage (BBCH 16) and the flag leaf stage (BBCH 39). In a single spraying, 1 dm^3 ha^{-1} of foliar fertilizer (a total of 2 dm^3 ha^{-1} during the plants' vegetation period) and 250 dm^3 ha^{-1} of working fluid were used. Spraying was carried out in the autumn and in the spring, in the morning hours, following fertilizer dose conversion to the plot surface area (15 m^2).

The field experiment was conducted on brown soil, quality class IIIa, good wheat complex, with a silty particle size distribution. Every year, soil samples were taken for chemical analysis prior to sowing. The soil chemical analysis was performed at an accredited laboratory of the District Chemical and Agricultural Station in Rzeszów, in accordance with Polish standards (PN-ISO 10390:1997, PN-R-04023:1996, PN-R-04022:1996+Az1:2002P, PN-R-04020:1994/Az1:2004, PN-R-04017:1992, PN-R-04016:1992, PN-R-04019:1993, PN-R-04021:1994, PN-R-04018:1993, soil organic matter from Corg. conversion). The soil was characterized by a slightly acidic pH and medium humus content. High levels of absorbable macronutrients (P, K, Mg) and medium levels of absorbable micronutrients (Fe, Zn, Mn, Cu, B) were found (Table 1).

Table 1

Soil chemical analysis (30 cm)

Parameter	Unit	2021	2022	2023	Contents
pH in KCl	-	6.4	6.0	5.9	slightly acidic
Organic matter	(%)	1.6	1.4	1.4	medium
P	(mg kg^{-1} soil)	79.8	76.7	71.1	high
K		201.7	200.0	183.4	high
Mg		82.0	77.0	75.0	high
B		1.5	1.7	1.5	medium
Mn		588.0	496.0	501.0	medium
Cu		4.2	3.8	3.6	medium
Zn		11.5	13.7	14.8	medium
Fe		2386.0	2086.0	1963.0	medium

Weather conditions (Figure 1) are given based on data from the University of Rzeszów meteorological station, located 10 km away from the experiment plot. Rainfall levels varied during the study seasons. The lowest rain-

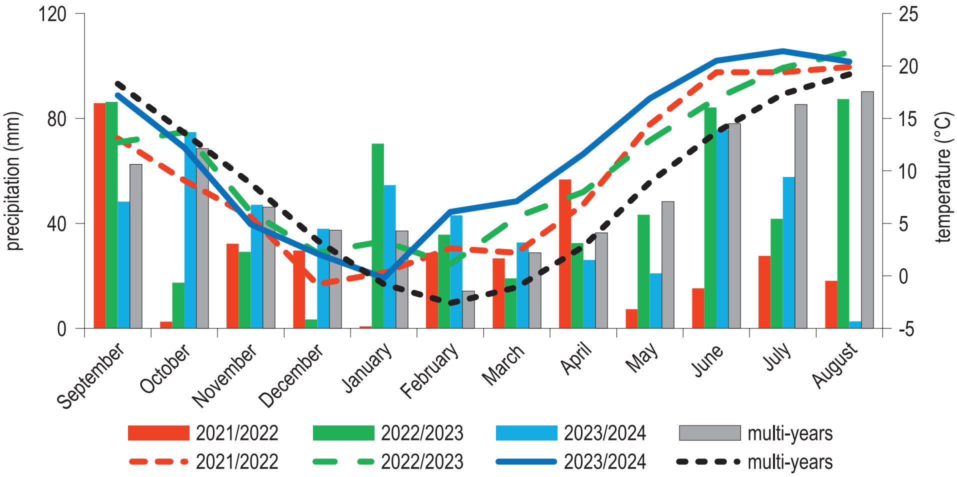

Fig. 1. Weather conditions in the years of research

fall, compared to multi-year data, was recorded in 2022 in the period from May to July. Additionally, temperatures in the autumn vegetation period remained below, and in the summer above the multi-year average.

The preceding crop each year was winter rapeseed. After its harvest, soil disking, NPK mineral fertilization (20 N kg ha^{-1}, 26,2 kg ha^{-1} P, 74,7 kg ha^{-1} K), and pre-sow ploughing (18 cm) were carried out. Sowing was carried out in the last ten days of August, in the amount of 340 grains per m^2. The row spacing was 12.5 cm, and the sowing depth was 3 cm. The seeds were treated with the Gizmo 060 FS formulation – 50 ml 100 kg^{-1}.

In spring, nitrogen fertilization (ammonium nitrate 34% N) was applied in two doses: 80 N kg ha^{-1}, at the beginning of vegetation, and at 70 N kg ha^{-1}, in the shooting stage (21 BBCH).

Plant protection treatments were performed with preparations approved for the protection of winter wheat, following prior inspection of the plantation. The dates and doses of the chemical preparations were in accordance with the manufacturers' recommendations. Chemical spraying was carried out using a tractor sprayer, with a fluid volume of 200 to 300 L ha^{-1}. The following preparations were used: Komplet 560 SC (diflufenican, flufenacet), Huzar Activ Plus (2,4-D iodosulfuron-methyl-sodium, thiencarbazone-methyl, mefenpyr-diethyl), Cyperkill Max 500 EC (cypermethrin), Ascra Xpro 260 EC (bixafen, fluopyram, prothioconazole), Soligor 425 EC (prothioconazole, spiroxamine, tebuconazole), Moddus 250 EC (trinexapac-ethyl). In spring, the herbicide Mustang 306 SE (florasulam, 2,4-D) and the fungicide Artea 330 EC (propiconazole, cyproconazole) were applied.

Soil plant analysis development (SPAD) was measured using the SPAD 502P chlorophyllometer (Konica Minolta, Japan). Measurements were made in the evening hours, on 10 flag leaves (BBCH 41) of each plot.

Prior to harvest, the number of spikes per 1 m² was counted. After that, 20 spikes were taken for biometric measurements and determination of the grain number per spike and the thousand grain weight (g). Harvest was carried out with a plot harvester in the first or second ten days of August. The grain weight was converted into the yield from 1 ha, assuming a moisture content of 14%, and then correcting it for the missing spikes taken for biometric measurements.

The grain protein content was determined using the near-infrared method on the FT-LSD MPA spectrometer (Bruker, Germany) at the laboratory of the University of Rzeszów Department of Crop Production. To determine the individual elements, the grain samples were mineralized in HNO_3: $HClO_4$: H_2SO_4 at a ratio of 20: 5: 1, in an open system in a Tecator heating block (FOSS, Denmark). The content of macroelements and microelements in the samples was determined by atomic absorption spectroscopy (FAAS) using a Hitachi Z-2000 spectrophotometer (Tokyo, Japan). The vanadium molybdenum method was used to determine phosphorus on a Shimadzu UV-VIS spectrophotometer (Kyoto, Japan).

The results were subjected to statistical examination with an analysis of variance (ANOVA). The significance of differences between mean object values of individual features was determined based on the Tuckey's confidence intervals at the level of significance of $p \leq 0.05$. If there was no interaction between the tested factor and the years, the results were given as averages for the years of the study. The calculations were made using the TIBCO Statistica 13.3.0 statistical software.

RESULTS AND DISCUSSION

Winter wheat yields varied over the research years. In 2022, the grain yield reached 7.92 t ha^{-1}, being higher by 1.4 t ha^{-1} and 0.67 t ha^{-1} in 2023 and 2024, respectively.

The largest increase in grain yield (Table 2) was obtained after the application of Cu and Mn, an effect which repeated in the research years. The difference compared to the control treatment was 0.19 t ha^{-1} and 0.15 t ha^{-1}, respectively. Fe and Zn spraying was less effective but significantly better compared to the control. The results of foliar fertilization with Mo and B were smaller than expected.

Variation in wheat yields over years of research was also demonstrated by other authors (Sobolewska et al. 2020, Jarecki 2021), which resulted from variable habitat conditions, mainly the sum of precipitation and average air temperatures. Previous research indicates that the use of foliar fertilizers generally has a positive effect on the volume and quality of wheat grain yield. This was mainly due to the increase in yield components and the

Table 2

Grain yield in harvest years (t ha^{-1})

Foliar fertilization (A)	Harvest year (B)			Mean
	2022	2023	2024	
control	7.82^{c}	9.21^{c}	8.49^{c}	8.51^{c}
Fe	7.91^{ab}	9.31^{bc}	8.59^{bc}	8.60^{ab}
Cu	8.01^{a}	9.42^{a}	8.68^{a}	8.70^{a}
Mn	7.96^{a}	9.38^{a}	8.64^{a}	8.66^{a}
Mo	7.88^{bc}	9.29^{bc}	8.56^{bc}	8.58^{bc}
B	7.89^{bc}	9.30^{bc}	8.58^{bc}	8.59^{bc}
Zn	7.94^{ab}	9.35^{ab}	8.62^{ab}	8.64^{ab}
Mean	7.92^{C}	9.32^{A}	8.59^{B}	8.61
AxB interaction	significant interaction			

increase in protein content in the grain. (Gul et al. 2011, Zoz et al. 2012). Belcar et al. (2021) proved that foliar fertilization increased grain yield from 0.49 to 0.64 t ha^{-1} compared to the control object, which is a better result than ours.

Foliar fertilization had no significant impact on the pre-harvest spike density compared to the control treatment. The grain number was the highest after the application of Cu and Mn, and the thousand grain weight was the highest after spraying with Cu, Mn, and Zn. The grain protein content was increased through the application of Cu, Mo, Mn and Zn. The differences were statistically significant (Table 3).

Table 3

Yield components and total protein content in grain, mean over the years

Foliar fertilization	Spike density (pieces m^{-2})	Number of grains in a spike	Thousand grain weight (g)	Total protein (% DM)
control	570.3^{a}	41.2^{b}	36.2^{b}	13.2^{b}
Fe	571.0^{a}	41.4^{ab}	36.4^{ab}	13.3^{ab}
Cu	571.3^{a}	41.6^{a}	36.6^{a}	13.4^{a}
Mn	571.7^{a}	41.5^{a}	36.5^{a}	13.5^{a}
Mo	570.8^{a}	41.4^{ab}	36.3^{ab}	13.4^{a}
B	570.1^{a}	41.4^{ab}	36.4^{ab}	13.3^{ab}
Zn	570.3^{a}	41.3^{ab}	36.7^{a}	13.5^{a}

Arif et al. (2006) proved that foliar application of nutrients favorably influenced the number of spikes per m^{-2}, the weight of a thousand grains, and the yield. These authors recommend two or three foliar sprays during the wheat vegetation stage. Results of the research conducted by Nadim et al. (2012) showed that the application of B resulted in an increase in the number of spikes, the number of grains per spike, and the grain yield. Foliar fertilization with Fe and Mn also brought good results, while fertilization with Zn and Cu brought the poorest results. It should therefore be noted that the results of foliar fertilization in studies are not always unambiguous.

Yadav et al. (2021) proved that Zn foliar fertilization significantly increased yield components compared to the control treatment. Research conducted by Jarecki (2021) shows that multi-component foliar spraying increased both the wheat yield and the grain protein content.

The applied foliar fertilization variants modified the content of some macronutrients in the wheat grain. Mn and Br increased the phosphorus content compared to Fe and Zn. Fe increased the potassium content, and Mn, Cu and B decreased the potassium content. Cu only lowered the magnesium content. Mo, B and Zn increased the calcium content, while Cu decreased it (Table 4).

Table 4

Content of macroelements in grain (g kg^{-1}), average over the years

Foliar fertilization	P	K	Mg	Ca
control	4.3^{ab}	3.41^{ab}	0.88^{a}	0.36^{ab}
Fe	4.1^{bc}	3.67^{a}	0.86^{a}	0.36^{ab}
Cu	4.3^{ab}	3.36^{bc}	0.74^{b}	0.32^{b}
Mn	4.4^{a}	3.36^{bc}	0.79^{ab}	0.35^{ab}
Mo	4.3^{ab}	3.46^{ab}	0.86^{a}	0.39^{a}
B	4.4^{a}	3.35^{bc}	0.85^{a}	0.39^{a}
Zn	4.0^{b}	3.46^{ab}	0.89^{a}	0.39^{a}

In the experiment conducted by Jarecki et al. (2017), triple foliar fertilization of wheat increased the ash and Mg contents in the grain compared to the control treatment and increased the Cu and Zn contents compared to a single foliar application and to the control treatment. Roşculete et al. (2023) reported that a single foliar fertilization treatment did not significantly affect the content of macroelements and microelements in the grain. Therefore, they recommend two or more sprays during the wheat growing period.

Foliar fertilization differentiated the micronutrient content in the wheat grain. The variant with foliar application of Cu, Mn and Zn lowered the iron content. The application of Fe, Mn and Zn reduced the copper content. In turn, Fe and Cu reduced the content of manganese while Zn increased the content of this micronutrient in the grain (Table 5).

Table 5

Content of microelements in grain (mg kg^{-1}), average over the years

Foliar fertilization	Fe	Cu	Mn	Zn
control	43.5^{a}	2.63^{a}	31.9^{a}	33.3^{b}
Fe	43.4^{a}	2.44^{c}	29.4^{b}	32.6^{b}
Cu	39.7^{b}	2.66^{a}	29.8^{b}	32.6^{b}
Mn	40.6^{b}	2.53^{bc}	31.8^{a}	32.7
Mo	41.4^{ab}	2.56^{ab}	31.5^{a}	33.1^{b}
B	43.5^{a}	2.63^{a}	31.9^{a}	33.3^{b}
Zn	40.2^{b}	2.53^{bc}	30.4^{ab}	36.6^{a}

Chwil (2014) reports that foliar fertilizers had a greater impact on the yield and gluten content than on the mineral composition of winter wheat grain and straw. Ram et al. (2024) proved that spraying with Zn significantly increased the content of this micronutrient in the wheat grain. Sobolewska (2020) found the highest concentrations of Zn, Mn and K in the leaves and grains of wheat double fertilized with Zn and Mn. İslamzade et al. (2025) demonstrated a significant increase in the content of N, P, K and of micronutrients such as Fe, Zn and Mn after the applied foliar fertilization compared to the control treatment. Hao et al. (2021) and Silva et al. (2025) showed that foliar application of Zn significantly improved the concentration of this micronutrient in grains, both in cultivars and in local varieties. However, the application of Fe did not bring the expected results.

Measurement of the plant nutritional status (SPAD) showed that foliar fertilization with Cu and Mn was most effective. The application of Fe and Zn resulted in less pronounced results, but these were still significantly better than those obtained in the control treatment. On the other hand, spraying with Mo and B produced statistically similar results to those in control (Figure 2).

In the experiments conducted by Jarecki (2021), the applied multi-component foliar fertilizers caused a significant increase in the leaf greenness index (SPAD). Therefore, they recommend more intensive variants of micronutrient application in the cultivation of winter wheat.

The content of macroelements and microelements in grain was negatively correlated with yield, except for Zn. The strongest negative coefficients were calculated for Fe and Mg. This is the result of the so-called dilution effect at high grain yield. Debicki et al. (1989) showed that the increase in rye yield resulted in a decrease in the grain P content.

The research conducted indicates that foliar fertilization with micronutrients should be recommended for agricultural practice. However, the effectiveness of such treatments will depend on numerous agro-environmental factors.

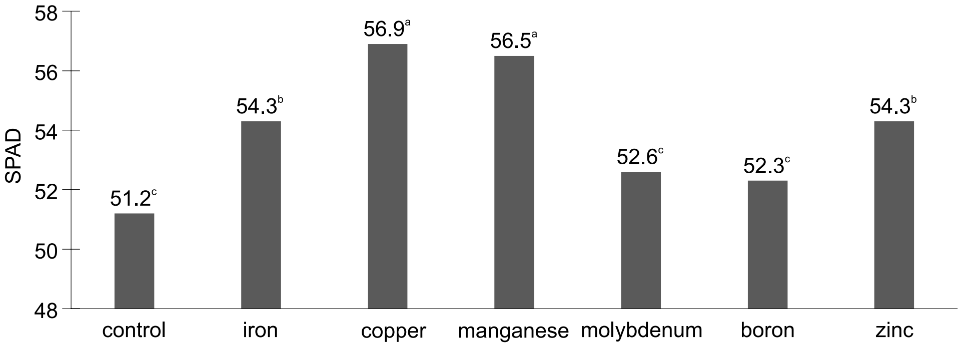

Fig. 2. Measuring the nutritional status of plants (Soil Plant Analysis Development – SPAD)

Table 6

Correlation coefficients (*r*) showing the relationship between yield and mineral content in grain

	Yield	P	K	Mg	Ca	Fe	Cu	Mn	Zn
Yield	1								
P	-0.063	1							
K	-0.208	-0.682	1						
Mg	-0.749	-0.478	0.437	1					
Ca	-0.486	-0.220	0.144	0.814	1				
Fe	-0.811	0.129	0.343	0.549	0.334	1			
Cu	-0.024	0.567	-0.813	-0.353	-0.233	-0.099	1		
Mn	-0.486	0.677	-0.620	0.209	0.388	0.260	0.394	1	
Zn	0.033	-0.669	0.006	0.540	0.537	-0.285	-0.116	-0.060	1

The correlation coefficients are significant at $p<0.05$.

CONCLUSIONS

The varied weather conditions over the course of the study seasons had a modifying effect on the winter wheat yields. The difference in grain yield between 2022 and 2023 was 1.4 t ha^{-1}.

The application of copper and manganese had the greatest impact on grain yields. Iron and zinc spraying was less effective. The results of foliar fertilization with molybdenum and boron were statistically similar to those in the control, which indicates that their uptake from the soil was sufficient.

The grain number per spike increased after spraying with copper and manganese and the thousand grain weight increased after application of copper, manganese and zinc.

The grain protein content was increased through spraying with copper, molybdenum, manganese and zinc. Foliar fertilization also modified the macro- and micronutrient content in grain, resulting from synergism or antagonism between the elements.

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Author contributions

W.J. – conceptualization, data curation, formal analysis, funding acquisition, methodology, resources, supervision, visualization, writing – original draft preparation, writing – review and editing. The author has read and agreed to the published version of the manuscript.

Conflicts of interest

The author ensures that he has neither professional nor financial connections related to the manuscript sent to the Editorial Board.

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