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ORIGINAL PAPER

Response of oilseed sunflower (*Helianthus annuus* L.) to foliar micronutrient fertilization[1]

Wacław Jarecki

Department of Crop Production
University of Rzeszów, Rzeszów, Poland

Abstract

Sustainable fertilization involves providing plants with optimal doses of necessary macro- and micronutrients. The demand for specific nutrients depends on various factors, including the cultivated species. Sunflower has moderate fertilization requirements, but certain elements are crucial for achieving high yield of good quality achenes. The purpose of this study was to evaluate the response of oilseed sunflower (variety MAS 81K) to foliar application of micronutrients: zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), and boron (B) in comparison to the control. A one-factor field experiment was conducted in 2022 and 2023, in a randomized block design. The soil at the experimental site was classified as Haplic Cambisol (Eutric) formed from loess, with moderate levels of Zn, Fe, Cu, Mn, and low levels of B. It was demonstrated that the weather conditions modified the effectiveness of foliar fertilization during the study years. The average achene yield in 2022 and 2023 was 3.41 t ha^{-1} and 3.57 t ha^{-1}, respectively. As a result of B fertilization, there was a significant increase in the flower head diameter and yield components. The difference in the achene yield obtained after B application was 0.29 t ha^{-1} in 2022 and 0.32 t ha^{-1} in 2023 compared to the control. Fertilization with Mo also had a positive effect on the achene yield compared to the control, while foliar application with Cu had a positive effect on the fat content. It was shown that the best results were primarily achieved with B application, followed by Mo and Cu.

Keywords: oil plant, nutrients, foliar fertilization, yield components, yield, quality of achenes

Wacław Jarecki, PhD DSc Eng., Department of Crop Production, University of Rzeszów, Zelwerowicza 4, 35-601 Rzeszów, Poland, e-mail: wjarecki@ur.edu.pl

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INTRODUCTION

Oilseed sunflower (*Helianthus annuus* L.) originates from North America, and it is currently one of the most important oilseed crops in the world. It was first domesticated by Native Americans, who used it as food and medicine, as well as for body painting in ceremonies (Fernández-Martínez et al. 2009, Kaya et al. 2012). A significant advantage of this species is its drought tolerance, which is crucial in the context of observed climate changes (Shi et al. 2024), as well as moderate nitrogen requirements (Jarecki 2022). However, Hanafy and Sadak (2023) demonstrated that prolonged drought stress reduces plant height, yield components, and overall yield. In such situations, these authors recommend using products that minimize water deficiency, such as foliar fertilizers. Sunflower is therefore an important species in crop rotation (Kussul et al. 2022) and additionally does not require intensive agronomic practices (Puttha et al. 2023), which is important for the development of sustainable agriculture.

Blamey et al. (1997) demonstrated that two factors, genetic and environmental (habitat) ones, determine the development and yield of sunflower (*Helianthus annuus* L.) plants. Some of the environmental factors that control and influence sunflower development and yield can be manipulated, while others cannot.

Among the agronomic factors, fertilization has the greatest impact on sunflower yield and quality. This species effectively utilizes both organic (Kimana et al. 2018, Sharma et al. 2008) and mineral fertilizers (Siddiqui et al. 2009, Škarpa et al. 2013, Oad et al. 2018). Chiurciu et al. (2020) and Grigore et al. (2009) reported that, in addition to soil fertilization, foliar application of fertilizers, especially micronutrients, is also possible. It can be carried out on soils deficient in micronutrients, such as calcareous (alkaline) soils, and in areas where water and thermal stress drastically limit plant access to nutrients. Previous studies (Tian et al. 2015, Omidi Nasab et al. 2021, Jarecki 2022) show that the use of macro- and micronutrients provides good results in sunflower fertilization.

A study by Kundu et al. (2023) has shown that in addition to nitrogen and macronutrients (P, K), micronutrients (Zn, B) have a beneficial effect on sunflower yield and its quality. As a result of their application, the hybrid variety tested showed an increase in the head diameter, number of achenes per head, achene weight per head, achene yield, and oil yield, which were 35.5%, 43.3%, 26.7%, 46.5%, and 51.3% higher, respectively, compared to the control. Farokhi et al. (2015) have concluded that micronutrients are required by plants in small quantities, yet they play a very important role in their physiological processes and, as a result, increase achene yield and quality. For sunflower, they considered Fe and Zn as the most important elements, with B playing a lesser role. According to Kaleri et al. (2019), the combination of N, Zn, and B in foliar fertilization significantly increased the number of leaves, stem thickness, head diameter, number of achenes per head, thousand-achene weight, and sunflower yield. Gebremedhin et al. (2015) believe that foliar fertilization with Fe and Zn is particularly important in calcareous soils, as their availability to plants is lower. On the other hand, Maqbool et al. (2023) have reported that sunflower is sensitive to B and Zn deficiencies, especially when grown in soils poor in these micronutrients. Sabudak et al. (2007) identified phytotoxic concentrations of Mn in sunflower leaves at some of the studied locations. On the other hand, significant nutrient deficiencies are often visible in the form of various chloroses or deformations in plants (Blamey et al. 1997, Nautiyal et al. 1999, Khurana and Chatterjee 2001).

Crops with broad leaves, such as sunflower, efficiently absorb mineral nutrients from foliar fertilizers, which makes such treatments cost-effective. A comparison of different sunflower fertilization methods demonstrated that foliar application was justified, which also applied to achene quality (Ebrahimian et al. 2010). Previous research has shown that foliar spraying of zinc (Li et al. 2019, Salem 2021, Poudel et al. 2024), iron (Ebrahimian et al. 2010), boron (Matoh, Ochiai 2005, Bhattacharyya et al. 2015, Singh et al. 2020), copper (Zengin, Kirbag 2007), manganese (László 2008) and molybdenum (Steiner, Zoz 2015) plays an important role in sunflower fertilization. However, the effect of applying these micronutrients in fertilization depends on various factors and not always provides consistent results (Poudel et al. 2023, 2024).

Poudel et al. (2023) pointed out that excessive Zn fertilization could negatively affect the content of other elements, such as Fe. Therefore, optimal and precise fertilization with nutrients is essential in crop cultivation, especially in terms of food safety and environmental protection.

The aim of the study was to evaluate the response of oilseed sunflower to the individual foliar application of selected micronutrients. The research hypothesis assumed that applying each micronutrient would produce favorable results compared to the control.

MATERIALS AND METHODS

Field conditions

The field experiment was conducted in 2022 and 2023 at the Agricultural Experimental Station in Boguchwała, Poland (21°57′E, 49°59′N). The factor under study was foliar fertilization with selected micronutrients compared to the control: control (spraying with water), zinc (Zn), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), boron (B).

The foliar fertilizers were purchased from Intermag sp. z o.o. (Olkusz, Polska). Each contained one main micronutrient: MIKROVIT® zinc – 112 g dm^{-3} Zn, MIKROVIT® iron – 75 g dm^{-3} Fe, MIKROVIT® copper – 75 g dm^{-3} Cu, MIKROVIT® manganese – 160 g dm^{-3} Mn, MIKROVIT® molybdenum – 33 g dm^{-3} Mo, BORMAX® boron – 150 g dm^{-3} B.

Foliar fertilization was carried out twice using a Kwazar Orion 9 L manual sprayer (Kwazar Sp. z o.o., Budy Grzybek, Poland) at the 6-leaf stage (BBCH 16) and during stem elongation (BBCH 32), which was consistent with the fertilizer manufacturer's recommendations. A single spraying involved the application of 1 dm^{-3} ha^{-1} of foliar fertilizer (a total of 2 dm^{-3} ha^{-1} during the growing season) and 250 dm^{-3} ha^{-1} of working solution. The sprayings were conducted in the morning hours, with the fertilizer dose calculated based on the plot area.

The experiment was conducted in a randomized block design with four replicates, using the variety MAS 81K (MAS Seeds S.A., Haut-Mauco, France). This variety is distinguished by early maturity, stable yield, and a high linoleic acid content.

Soil conditions

The experiment was set up each year on a Haplic Cambisol (Eutric) formed from loess (IUSS Working Group WRB 2022). Chemical analysis of soil samples was conducted by an accredited laboratory of the Regional Chemical and Agricultural Station in Rzeszów, according to Polish standards. The soil (Table 1) was characterized by a slightly acidic pH, moderate humus content, and low N_{min} levels. The content of available macronutrients (P, K, Mg) was high, while the levels of micronutrients were moderate (Fe, Zn, Mn, Cu) or low (B). It should be noted that soil molybdenum analyses are not standard procedures in Poland.

Table 1

Soil analysis under field experiment (0-30 cm)

Parameter	Unit	2022	2023
pH	(1 mol L^{-1} KCl)	6.2	6.0
Humus	%	1.4	1.2
N_{min}	(kg ha^{-1})	56	54
P	(mg kg^{-1} soil)	78.0	73.7
K		176.8	172.6
Mg		73	71
Fe		1853	2153
Zn		11.3	14.8
Mn		408	453
Cu		4.8	5.1
B		0.9	1.1

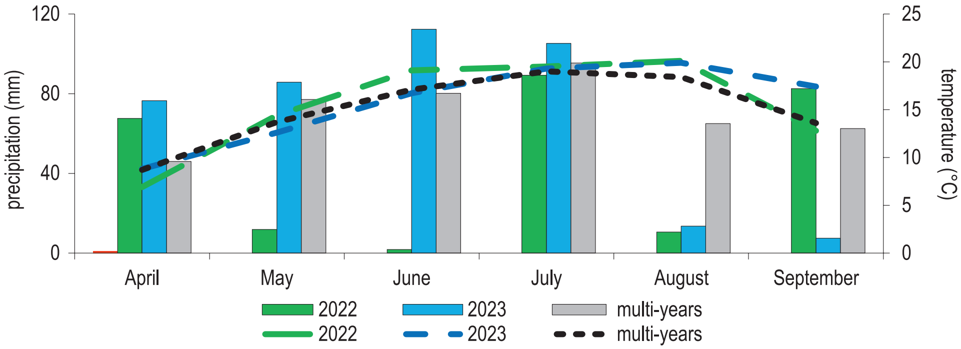

Fig. 1. Weather conditions during the plant vegetation period.
The bars show precipitation and the lines show temperature.

Weather conditions

The weather conditions (Figure 1) were determined according to the records of the Meteorological Station in Boguchwała, located approximately 0.5 km from the experimental field. The weather varied during the study years. The total rainfall was very low in May, June, and August 2022. Conversely, in 2023, low precipitation was recorded in August and September, while it was exceptionally high in June and July. Air temperatures in August were significantly higher compared to the long-term average.

Agrotechnical treatments

The preceding crop was corn for grain, followed by mineral fertilization and winter plowing after harvest. Phosphorus and potassium fertilization was carried out in the fall at doses of 26.16 kg ha^{-1} P (single superphosphate) and 74.7 kg ha^{-1} K (potassium chloride). In the spring, the field was harrowed, and before sowing, a cultivator was used along with nitrogen fertilization. Urea with a urease inhibitor (46% N) was used for nitrogen fertilization in a single spring dose of 80 N kg ha^{-1}. Sowing was carried out in late April (28.04.2022 and 26.04.2023) using a precision seeder. The achenes were treated with Maxim 025 FS (fludioxonil) according to the manufacturer's recommendations. The row spacing was 50 cm, and the sowing depth was 4 cm. Eight viable achenes were sown per square meter. The area of a single plot was 20 m^2 (4 m × 5 m). Plant protection treatments were carried out using products approved for sunflower protection during the study years (pendimethalin, aclonifen, metolachlor, azoxystrobin, difenoconazole). The doses and dates of chemical product applications were consistent with manufacturer's recommendations.

Biometric measurements

Before harvesting, 20 plants were sampled for biometric measurements (number of achene per head). The thousand-achene weight (TSW) was measured and corrected for a fixed moisture content of 9%. The harvest was conducted with a field harvester during the full maturity stage, which occurred in the second half of September. Achene yield was calculated per hectare, accounting for a fixed moisture content of 9%.

Chemical analyses

Achenes for chemical analyses were collected from each plot during harvest. The chemical composition of the whole achenes (unhulled) was determined with near-infrared spectroscopy using a FT-LSD MPA spectrometer (Bruker, Germany) at the Department of Crop Production of the University of Rzeszów. To determine the individual microelements, achene samples were mineralized in HNO_3: $HClO_4$: H_2SO_4 at a ratio of 20:5:1, in an open system using a Tecator heating block (FOSS, Denmark). The content of Zn, Mn, Fe and Cu in the samples was determined by atomic absorption spectroscopy (FAAS) using a Hitachi Z-2000 apparatus (Tokyo, Japan).

Statistical calculations

The results were statistically analyzed using analysis of variance (ANOVA), implemented in Statistica 13.3.0 (TIBCO Software Inc., Palo Alto, CA, USA). Significance of differences between treatments was verified by the Tukey test.

RESULTS AND DISCUSSION

Biometric measurements and yield components

Foliar B fertilization increased the flower head diameter compared to the control, and so did fertilization with Zn, Fe, and also Cu but only in 2022. In the first year of the study, a higher number of achenes per flower head was recorded after Mo and B application compared to the control. In the second year of the study, the same results were obtained for B, but not for Mo. The most favorable effect on MTA (mass of a thousand achenes) was observed for B application compared to the control, followed by Fe, Cu, and Mn. The results of the measurements of yield components were significantly higher in 2023, except for TSW (Table 2). The diameter of sunflower heads in our study was lower than the range of 20-25 cm reported by Kaya et al. (2012). Farzanian et al. (2010) demonstrated that foliar application of B improved the traits tested, including the number of achenes per head. However, the best results were obtained after the combined application of four micronutrients.

Table 2

The influence of foliar fertilization on selected plant parameters and yield components

Years	Foliar fertilization	Head diameter (cm)	Number of achenes in the head	Mass of a thousand achenes (g)
2022	control	15.5±0.94[a]	990.5±18.7[a]	47.5±1.32[a]
	zinc	15.8±0.68[a]	999.9±22.7[ab]	49.0±1.95[ab]
	iron	15.7±0.59[a]	998.5±21.2[ab]	48.5±1.51[a]
	copper	16.0±0.80[a]	998.3±19.2[ab]	48.4±1.62[a]
	manganese	16.8±0.34[ab]	996.4±17.8[ab]	48.6±1.77[a]
	molybdenum	17.0±0.80[ab]	1002.6±19.3[b]	50.0±1.95[ab]
	boron	17.9±0.61[b]	1003.9±17.1[b]	51.0±1.95[b]
2023	control	17.0±.018[a]	1003.3±15.4[a]	48.7±0.69[a]
	zinc	17.7±0.22[a]	1013.2±19.2[ab]	50.4±1.60[ab]
	iron	17.6±0.21[a]	1009.9±10.5[ab]	49.9±1.16[a]
	copper	17.9±0.26[ab]	1011.1±18.4[ab]	49.9±1.11[a]
	manganese	18.3±0.18[ab]	1011.7±16.9[ab]	49.8±1.39[a]
	molybdenum	18.7±0.40[ab]	1013.9±19.6[ab]	51.4±1.60[ab]
	boron	19.0±0.41[b]	1019.2±20.2b	52.4±1.60[b]
2022		16.39±0.72[A]	16.39±0.72[A]	998.59±19.6[A]
2023		18.03±0.21[B]	18.03±0.21[B]	1011.76±16.3[B]

Achene yield

Foliar B application significantly increased sunflower achene yield compared to the control, Fe, Cu, and Mn. The application of Mo increased the yield, but this result was only statistically significant compared to the control. In 2022, the achene yield ranged from 3.28 t ha^{-1} to 3.57 t ha^{-1}, while in 2023, it ranged from 3.42 t ha^{-1} to 3.74 t ha^{-1} (Figure 2). The resulting

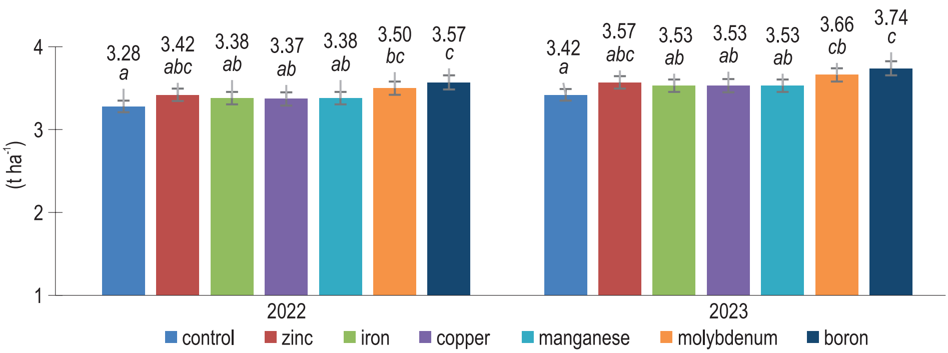

Fig. 2. Yield of achenes (t ha^{-1}). Different lower case letters indicate significant differences between plants fertilized with particular microelements (p<0.05)

increase in achene yield after B application was 0.29 t ha^{-1} in the first year of the study and 0.32 t ha^{-1} in the second year of the study. The observed effect with B application may have been attributed to the low soil levels of this element. Al-Amery et al. (2011) demonstrated that B reduced the number of empty achenes. The application of B is considered valuable from an agronomic standpoint, especially during the early flowering stage of sunflower. Faisal et al. (2020) reported that B fertilization had the most positive effect on sunflower yield. Steiner and Zoz (2015) demonstrated that Mo foliar application during the eight-leaf stage improved nitrogen uptake by the plants, which consequently increased MTA and yield. Fertilization Zn, especially in soils deficient in this element, can positively affect the size and quality of sunflower yield, as demonstrated by Keerio et al. (2020). Chiurciu et al. (2020) recommended applying multicomponent foliar fertilizers, as they achieved increases in achene yields ranging from 292 to 587 kg ha^{-1}. Interesting results were also presented by Gormus and Barutcular (2016), who found that boron fertilization did not yield consistent results, as it depended on the study location and, consequently, local environmental conditions.

Chemical analyses

Foliar fertilization with micronutrients modified the fat and fiber contents in the achenes but had no effect on the protein and ash contents. In 2022, foliar application of Cu significantly increased the fat content in achenes compared to the applications of Zn, Fe, Mn, and B. In 2023, similar results were obtained, but additionally, Cu fertilization was more effective than Mo. A higher fiber concentration was observed in the control group and after applying Zn compared to the other treatments, but the differences were not always statistically significant (Table 3). Keerio et al. (2020) have suggested that Zn fertilization significantly increases sunflower yield and quality, especially in regions where there are deficiencies of this micronutrient in soils. Al-Doori (2014) showed that the availability of most micronutrients was low in calcareous or alkaline soils, and in such conditions, Zn foliar application significantly increased oil and protein yields. In a study by Nautiyal et al. (1999) and Zengin and Kirbag (2007), achene oil content was favorably affected by Cu fertilization; however, the dosage should not be excessively high to avoid toxicity to sunflower plants. Mekki (2015) and Abido and Abo-El-Kheer (2020) demonstrated that B significantly increased many of the sunflower traits tested, including the achene fat content. However, García Lamothe and Quincke (2012) found that boron fertilization did not significantly affect achene yield or oil content. This effect was the result of sufficient levels of this micronutrient in the soil.

Microelement content in achenes

As anticipated, foliar fertilization influenced the micronutrient content in sunflower achenes, with the effects varying between study years. In 2022,

Table 3

The effect of foliar fertilization on the chemical composition of whole achenes (g kg^{-1} d.m.)

Years	Foliar fertilization	Fat	Protein	Ash	Fiber
2022	control	493±10.8*	125±3.9*a*	230±3.9*a*	146±5.8*b*
	zinc	483±10.8*a*	135±3.9*a*	238±4.2*a*	145±6.1*b*
	iron	481±16.9*a*	129±4.7*a*	235±3.9*a*	136±5.8*a*
	copper	508±9.8*b*	136±4.3*a*	230±3.9*a*	138±7.5*ab*
	manganese	473±10.8*a*	135±5.2*a*	248±4.2*a*	138±8.6*ab*
	molybdenum	486±9.6*ab*	131±7.3*a*	237±4.3*a*	135±5.6*a*
	boron	483±10.8*a*	130±6.0*a*	232±3.9*a*	130±5.0*a*
2023	control	515±8.7*ab*	110±7.1*a*	211±3.3*a*	144±4.9*b*
	zinc	505±8.7*a*	120±7.1*a*	218±3.4*a*	142±4.6*b*
	iron	502±4.5*a*	115±6.8*a*	214±3.3*a*	135±6.1*ab*
	copper	525±8.7*b*	121±6.6*a*	211±3.3*a*	134±4.9*ab*
	manganese	493±5.1*a*	120±4.1*a*	220±3.3*a*	135±6.4*ab*
	molybdenum	503±5.1*a*	116±8.9*a*	217±3.7*a*	133±4.9*ab*
	boron	505±8.7*a*	114±10.1*a*	214±3.2*a*	127±8.8*a*
2022		487±10.2A	487±10.2*A*	132±4.2*B*	236±4.0*A*
2023		507±7.5B	507±7.5*B*	117±6.2*A*	215±3.4*A*

* Different lower case letters indicate significant differences between plants fertilized with particular microelements ($p<0.05$). Different upper case letters indicate significant differences ($p<0.05$) between study years.

Mn application increased the content of this element in the achenes compared to Fe and Mo applications. Leaf fertilization with Cu also increased the content of this element in sunflower achenes compared to the other micronutrients, and the control. In 2023, an increase in the content of Zn and Fe in sunflower achenes was observed following their application. However, while the difference in Fe concentration was statistically significant compared to the other applied micronutrients, it was not significant in comparison to the control (Table 4). Jyothi et al. (2018) confirmed that micronutrient fertilization, such as B, positively influenced the uptake of macroelements by plants. On the other hand, Ebrahimian et al. (2010) demonstrated that foliar application of Zn and Fe increased the content of these elements in the leaves, but did not affect the levels of N, P and K. Khurana and Chatterjee (2001) proved that Zn deficiency reduced its content in the leaves, while increasing phosphorus levels. Sakouhi and Ferjani (2022) confirmed that excess Cu disrupted the mineral composition of plant tissues and reduced their K, Mg, Zn, and Mn levels.

Table 4

The influence of foliar fertilization on the content of microelements (mg kg^{-1})

Years	Foliar fertilization	Zn	Mn	Fe	Cu
2022	control	30.5±1.66*	17.9±0.91*ab*	49.3±1.61*a*	15.7±0,78*a*
	zinc	30.9±1.69*a*	17.2±1.16*ab*	48.2±1.62*a*	15.0±0,76*a*
	iron	29.6±1.31*a*	16.1±1.12*a*	49.9±1.52*a*	15.1±0,75*a*
	copper	30.1±1.71*a*	17.0±1.25*ab*	48.3±1.61*a*	17.2±1,25*b*
	manganese	30.1±1.81*a*	18.3±0.63*b*	48.1±1.60*a*	15.0±0,64*a*
	molybdenum	30.2±2.01*a*	16.8±1.10*a*	48.7±2.04*a*	14.9±0,94*a*
	boron	29.9±2.16*a*	17.0±1.82*ab*	48.4±1.47*a*	15.7±0,78*a*
2023	control	32.5±1.29*a*	18.3±0.98*a*	52.0±1.35*ab*	16.9±0,85*a*
	zinc	34.1±0.98*b*	17.9±0.95*a*	50.7±1.36*a*	16.3±1,37*a*
	iron	30.5±1.39*a*	16.7±0.75*a*	53.9±1.32*b*	16.4±1,07*a*
	copper	32.5±1.05*a*	16.6±0.78*a*	50.2±1.35*a*	17.8±1,43*a*
	manganese	32.8±1.04*a*	18.4±1.34*a*	50.5±1.54*a*	16.3±0,74*a*
	molybdenum	32.6±1.71*a*	18.1±0.45*a*	51.2±1.35*a*	16.4±1,08*a*
	boron	32.8±1.70*a*	18.1±1.62*a*	51.0±1.02*a*	16.9±0,85*a*
2022		30.2±1,75A	30.2±1,75*A*	17.2±1.18*A*	48.7±1.61*A*
2023		32.5±1,56B	32.5±1,56*B*	17.7±0.68*A*	51.4±1.32*B*

* Different lower case letters indicate significant differences between plants fertilized with particular microelements ($p<0.05$). Different upper case letters indicate significant differences ($p<0.05$) between study years ($p<0.05$).

CONCLUSIONS

Foliar fertilization is an agronomic practice commonly used in crop cultivation. The effectiveness of this treatment depends on many factors, including plant species, chemical composition of the preparation, dosage and date of application, as well as soil and weather conditions. The results of the present field experiment demonstrated a significant response of sunflower to foliar application of individual micronutrients (Zn, Fe, Cu, Mn, Mo, B) compared to the control. The most favorable results were obtained following foliar B fertilization, but positive results were also achieved with the application of Mo and Cu. Weather conditions during the study years had a significant impact on the results of foliar fertilization. For these reasons, the results from the first year were not always reproducible in the second year. The average achenes yield in 2022 and 2023 was 3.41 t ha^{-1} and 3.57 t ha^{-1}, respectively. Achene quality was mainly affected by the application of Cu, followed by Mn, Fe, and Zn. The difference in achene yield obtained after B application was 0.29 t ha^{-1} in 2022 and 0.32 t ha^{-1} in 2023 compared to the control. The results of the current experiment demonstrated that the application of B was most beneficial, while the use of molybdenum (Mo) and copper (Cu) exerted a comparatively weaker effect. The application of the remaining micronutrients yielded results that were below expectations.

Author contributions

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

Conflicts of interest

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

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