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Influence of Foliar Application of Microelements on Yield and Yield Components of Spring Malting Barley

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Abstract: Barley is an economically important plant cultivated primarily for animal feed and in the brewing industry for the production of barley malt. Climate changes and an increase in grain demand result in a constant need to improve the volume and stability of cereal species yields and better use the potential of cultivars. In cereal production, an important aspect is the use of microelements, especially by foliar spraying. Microelements, as components or enzyme activators, play a significant role in plant growth and metabolic processes occurring in the cell. As a consequence, their availability is a factor determining plant development. The aim of this study was to determine the effect of foliar fertilization with selected microelements on the yield of two-row malting barley cultivars. In 2019–2021, a two-factor field experiment with barley was conducted in south-eastern Poland. The experimental factors were three spring barley cultivars (Baryłka, KWS Irina, and RGT Planet) of the brewing type and four single-component micronutrient fertilizers containing copper (Cu), manganese (Mn), molybdenum (Mo), and zinc (Zn). The foliar application of microelements resulted in improvements in selected elements of the yield structure and an increase in grain yield, and the effect depended on the fertilization applied. The highest grain yield was obtained from plots where fertilizer with Mo or Zn was used. Barley plants sprayed with Mo fertilizer developed the longest spikes and were characterized by the highest number of productive tillers per plant. The foliar application of Zn resulted in the formation of the highest number of spikes per unit area and grain uniformity. The RGT Planet cultivar was characterized by higher values of the measured parameters compared to Baryłka and KWS Irina.

Keywords: foliar fertilization; grain yield; *Hordeum vulgare* L.

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1. Introduction

Barley (*Hordeum vulgare* L.) belongs to the *Poaceae* family and is one of the longest-cultivated cereals in the world, important for food security. In terms of cultivated area, it is the fifth most popular crop and an important element of European agriculture. The largest barley grain producers are Russia, Australia, France, and Germany [1,2]. Barley is grown in high-production and low-input farming systems in a wide range of environments. Both spring and winter forms are available in cultivation [3–6]. Throughout the world, barley is grown primarily for animal feed and also for the production of barley malt used in brewing. About 2–5% of the grain is intended for direct human consumption. Numerous studies indicate that barley is one of the healthiest cereals in the human diet due to the high content of some important nutrients and beta-glucan [5,7,8]. There are two botanical types of barley: two-row and six-row genotypes. Traditionally, two-row malting barley has been grown in Europe [2].

Progressing climate change has a negative impact on the productivity of global agriculture; therefore, there is a need to expand the research on how to improve the yield of important crop species and better use the potential of cultivars. Nutrition and water availability are critical to the grain yield and quality of a cultivar in a variety of environments.

As the world population increases, the demand for cereal grains will increase; therefore, it is important to better understand the processes that determine the development, growth, and yield of cereal plants, including barley [2,9].

Previous research on barley fertilization has focused mainly on examining the role of macroelements in shaping the barley yield [10–13]. The most researched element in the cultivation of this species is nitrogen. Nitrogen is the most yield-producing ingredient in cereal fertilization, but it also significantly affects the suitability of grains for the brewing industry [12,14–22].

The availability of nutrients to plants depends on their contents in the soil, as well as on soil moisture, temperature, light, and climatic conditions [23]. An important aspect of grain agrotechnology is the use of microelements. It is known that all higher plants need six microelements, i.e., Mn, Fe, Cu, Zn, B, and Mo. Microelements are essential nutrients that are required in small amounts for the proper growth and development of plants [23,24]. They play a significant role in plant growth and metabolic processes in the cell. They are important components or activators of catalysts for many enzymatic processes, important both for yield formation (photosynthesis) and for grain germination in the malting process (respiration) [25–27]. Feeding plants with microelements can help maximize yields and is used as a method of plant biofortification [28]. In recent years, the occurrence of microelement deficiencies has become more and more frequent, and the rate of their reduction in the soil has been increased, among other factors, by leaching, liming acidic soils, growing plants with high nutritional requirements, and using marginal land for plant production. The problems of micronutrient deficiencies are also further enhanced by their high demand in modern crop cultivars [26,29,30].

A popular form of providing microelements to plants is foliar spraying, which became more widely used in the 1950s [31,32]. It involves applying nutrients, biostimulants, and other beneficial substances to the above-ground parts of plants, such as leaves and stems. The main advantage of foliar fertilization is the immediate absorption of the applied nutrients [28,33]. Using foliar fertilization, the losses that occur with soil fertilization due to the retardation and leaching of elements are avoided. Foliar doses can be lower than those applied to the soil, which is both economically and ecologically important. It is possible to combine foliar fertilization with plant protection treatments. This allows growers to reduce the number of treatments and financial expenditure on production. Fertilization with microelements helps alleviate abiotic stresses in plants [34]. Foliar application allows plants to be quickly supplied with nutrients in the case of both their deficiency in the soil and their difficult uptake, e.g., in the case of drought [33,35].

Foliar treatments with preparations containing microelements are used in the cultivation of many plant species, mainly in cereals [36,37], oil plants [38], and vegetables [39,40]. The response of a crop plant to the foliar supply of nutrients varies among different crop species, as well as among cultivars within the same species [41].

Due to the popularity of barley and the advantages of foliar fertilization, research on the impact of individual microelements on yield and their yield-producing characteristics should be expanded. There is a lack of information in the scientific literature regarding the effects of different microelements on malting barley. Among the microelements, copper, manganese, molybdenum, and zinc seem to be particularly important in cereal cultivation [37,42–44]. The aim of this study was to determine the effect of foliar fertilization with selected microelements on the yield of malting barley. A research hypothesis was established that states that foliar spraying with fertilizers containing microelements has a positive effect on yield components and causes an increase in grain yield.

2. Materials and Methods

2.1. Description of the Field Experiment

The field experiment was carried out in 2019–2021 in Reczpol (49°47′03″ N, 22°34′37″ E, south-eastern Poland). A two-factor experiment was set up using the split-block method with four repetitions. The experimental factors were as follows:

I. Cultivars of spring two-rowed barley of the brewing type:
- Baryłka (Hodowla Roślin Strzelce Sp. z o.o. Grupa IHAR, Strzelce, Poland);
- KWS Irina (KWS Lochów Polska Sp. z o.o., Prusy, Poland);
- RGT Planet (R.A.G.T. Semences Polska Sp. z o.o., Toruń, Poland).

II. Foliar fertilization with microelements:
- Control—without fertilization;
- Copper (Cu);
- Manganese (Mn);
- Molybdenum (Mo);
- Zinc (Zn).

The dates of the treatments performed in barley cultivation are presented according to the BBCH scale (Biologische Bundesanstalt, Bundessortenamtund Chemische Industrie) [45].

Mikrovit® single-component fertilizers from Intermag were used as the sources of microelements applied to the foliage. During the shooting phase, the foliar spraying of microelements in the form of aqueous solutions (BBCH 30–32) was carried out. The treatment was performed in windless weather using a pressure sprayer. Doses were determined according to the manufacturer's recommendations. The composition and doses used are presented in Table 1.

Table 1. Chemical compositions of the foliar fertilizers.

Fertilizer	Composition (g·L^{-1})	Chemical Form	Dose (L·ha^{-1})
MIKROVIT® MIEDŹ	75	Copper sulfate $CuSO_4$	2
MIKROVIT® MANGAN	160	Manganese sulfate $MnSO_4$ (65 g) and manganese nitrate $Mn(NO_3)_2$ (95 g)	2
MIKROVIT® MOLIBDEN	33	Ammonium molybdate $(NH_4)_6Mo_7O_{24}$	1
MIKROVIT® CYNK	112	Zinc sulfate $ZnSO_4$	2

In the experiment, NPK fertilization was used each year at doses of 50 kg·ha^{-1} N, 60 kg·ha^{-1} P_2O_5, and 90 K_2O kg·ha^{-1}. In spring, before sowing, Polifoska® 6 fertilizer (6% N, 20% P_2O_5, 30% K_2O, 7% SO_3) was applied at a dose of 300 kg·ha^{-1} and Ammonium nitrate 32 at a dose of 100 kg·ha^{-1} (32% N). In order to ensure the basic requirements of plants in terms of microelements in the tillering phase (BBCH 25–27), the multi-ingredient foliar preparation Opti Zboża (Chemirol) was used at a dose of 3 kg·ha^{-1}. The composition of the preparation in g·kg^{-1} was as follows: N—140; P_2O_5—160; K_2O—160; MgO—30; SO_3—180; Cu—3; Fe—1.5; Mn—5; Mo—0.4; Zn—1.5. In each year of the study, sowing was carried out in the first 10 days of April (6 April 2019, 2 April 2020, 8 April 2021). The certified seed material of the tested cultivars was obtained from breeding companies. The sowing rate was 165 kg·ha^{-1}. The seeds were sown at a 12 cm row spacing to a depth of 3 cm. The barley forecrop in each year of the study was winter oilseed rape. The area of a single harvest plot was 15 m^2. The dates and doses of the plant protection products and growth regulators used in barley cultivation are presented in Table 2. Before harvesting, the number of spikes per m^2 was determined. The grain was harvested at full maturity (BBCH 89). In the years of the research, the harvest date was in the last 10 days of July (22 July 2019, 30 July 2020, 25 July 2021).

2.2. Characteristics of Soil Conditions

The experiment was established on Fluvic Cambisol (CMfv). The soil pH was slightly acidic (Table 3). The soil analysis was performed in an accredited laboratory of the Chemical and Agricultural Station in Rzeszów. The soil was characterized by a low phosphorus content, a high or medium potassium content, and a high magnesium content. The manganese, zinc, and molybdenum contents were average in all years of the study. The copper content was low in 2019 and average in subsequent years. Iron was at an average level in 2019 and 2020 and at a high level in 2021 (Table 3).

Table 2. Dates and doses of preparations used in barley cultivation.

Preparation		Dose		BBCH Phase
Fungicide	Funaben Plus 02WS	150	g per 100 kg of seed	-
	Fandango 200EC	1.0	$L \cdot ha^{-1}$	31–34
	Kier 450S	1.0		51–55
Herbicide	Mocarz 75WG	0.2	$kg \cdot ha^{-1}$	25–29
	Herbistar 200EC	0.5	$L \cdot ha^{-1}$	25–29
Growth regulator	Moddus 250EC	0.4		31–34
Insecticide	Delmetros 100SC	0.05		55 (only in 2019)

Table 3. The characteristics of the soil on which the field experiment was carried out.

Parameter	Year		
	2019	2020	2021
pH in 1 $mol \cdot dm^{-3}$ KCl	6.0	5.8	5.8
Soil Organic Carbon (%)	1.3	1.1	1.1
	Content of available forms $mg \cdot kg^{-1}$ soil		
Phosphorus (P_2O_5)	59	66	69
Potassium (K_2O)	220	160	188
Magnesium (Mg)	101	91	96
Copper (Cu)	2.2	2.4	3.7
Manganese (Mn)	164	396	225
Zinc (Zn)	5.0	10.3	20.0
Iron (Fe)	1080	1563	3824

2.3. Characteristics of Weather Conditions

Data on weather conditions are given according to measurements from the Meteorological Station located in Zadąbrowie (50.19′09″ N, 21.48′19″ E). On their basis, the average monthly temperatures and rainfall sums were calculated in the years of the field experiments. Precipitation and temperature values during the barley growing season are presented in Figure 1.

The water and thermal conditions during plant vegetation were characterized by calculating the hydrothermal coefficient of Sielianinow k. The average hydrothermal coefficients that characterize the weather patterns in particular years are presented in Table 4. The coefficient was calculated using the following formula:

$$k = \frac{P}{\Sigma t \cdot 0.1}$$

k—coefficient of Sielianinow;
P—total monthly precipitation (mm);
Σt—total of monthly daily temperatures (°C).
Hydrothermal conditions were characterized according to Skowera et al. [46] depending on the value of k:
$k \leq 0.4$—extremely dry (ed);
$0.4 < k \leq 0.7$—very dry (vd);
$0.7 < k \leq 1.0$—dry (d);
$1.0 < k \leq 1.3$—relatively dry (rd);

$1.3 < k \leq 1.6$—optimal (o);
$1.6 < k \leq 2.0$—relatively humid (rh);
$2.0 < k \leq 2.5$—humid (h);
$2.5 < k \leq 3.0$—very humid (vh);
$k > 3.0$—extremely humid (eh).

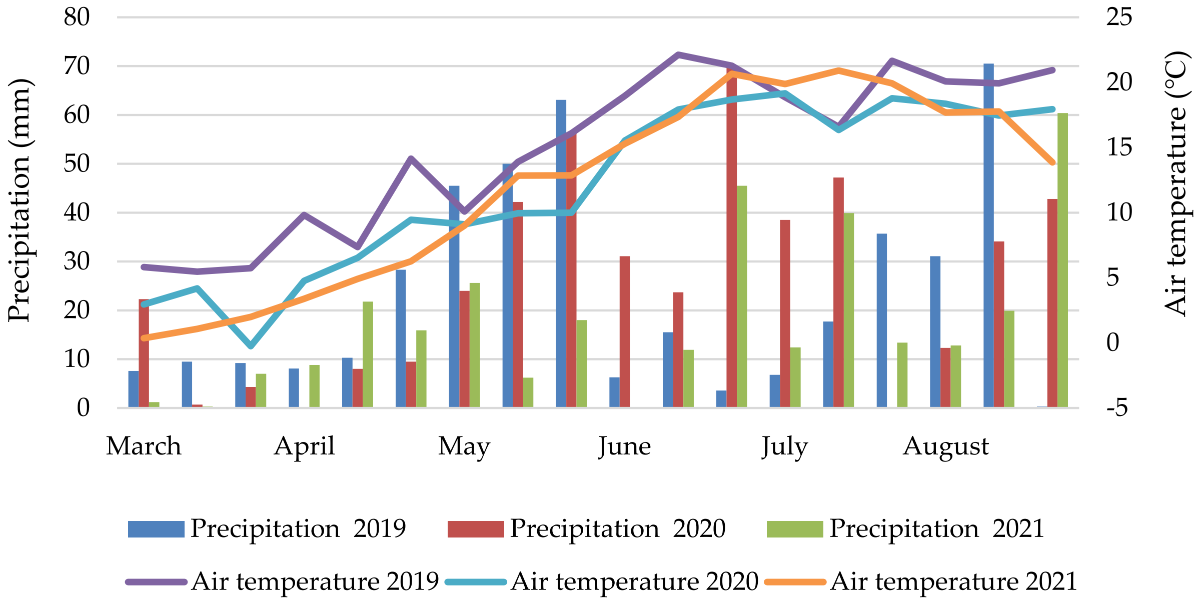

Figure 1. Weather conditions during the field experiment.

Table 4. Sielianinow coefficient (*k*) during barley vegetation.

Year	Month						Mean
	March	April	May	June	July	August	
2019	1.50 o	1.49 o	3.83 eh	0.41 vd	1.02 rd	1.62 rh	1.64 rh
2020	3.83 eh	0.84 d	4.09 eh	2.40 h	1.53 o	1.61 rh	2.38 h
2021	2.40 h	3.20 eh	1.39 o	1.08 rd	1.05 rd	1.83 rh	1.82 rh
Long-term * 1991–2020	3.81 eh	1.68 rh	1.83 rh	1.55 o	1.51 o	1.08 rd	1.91 rh

*—Calculated based on climatic standards for Rzeszów (50°02′01″ N, 22°00′17″ E) [47]; the Sielianinow coefficient (*k*) during the vegetation period in the years 2019–2021 (vd—very dry; d—dry; rd—relatively dry; o—optimal; rh—relatively humid; h—humid; eh—extremely humid).

The average values of the hydrothermal coefficient during barley vegetation in each year of the study indicate that these were years with quite high rainfall, with values close to the long-term average (Table 4). The wettest year was 2020. The most favorable weather conditions were recorded in March and April 2019, July 2020, and May 2021. The driest month was June 2019. Extremely humid conditions were recorded in May 2019, March and May 2020, and April 2021 (Table 4).

2.4. Laboratory Analyses of Yield

Before harvesting, 20 representative plants were randomly sampled from each plot to assess the biometric characteristics of plants and barley yield components, such as plant height (cm), spike length (cm), number of productive tillers per plant, grain weight per spike (g), and number of grains per spike. Thousand-grain weight (TGW) at 14% moisture content was determined using a grain counter (Sadkiewicz Instruments, Bydgoszcz, Poland) [48]. Grain yield (GY) per plot was calculated per hectare, taking into account 14% moisture content. The above-ground parts of the plants were weighed, and the ratio of grain yield to above-ground biomass yield, presented as the harvest index (HI), was calculated. Uniformity was assessed by sieving a 100 g grain sample through Vogel sieves on the SŻK

Sadkiewicz mechanical sorter for 3 min. The percentage ratio of the grain mass retained on sieves with diameters of 2.5 and 2.8 mm to the total mass of the sample was calculated [49].

2.5. Statistical Analysis

The data collected were statistically analyzed using the Statistica 13.1 (TIBCO Software Inc., Palo Alto, CA, USA) program. An analysis of variance (ANOVA) was performed for a two-factor split-block experiment. To determine and verify relationships, Tukey's post hoc test was performed at a significance level of 5%.

The relationships between the yield and its elements were determined on the basis of Pearson's simple correlation coefficients (r).

3. Results

3.1. Plant Height, Spike Length, and Productive Tillers

In the experiment, the height of the plants was in the range of 57.1–70.9 cm. Plants treated with foliar fertilizers were lower in height compared to control plots. After applying each of the microelements tested, a significant reduction in plant height was observed—on average by 6.7%—compared to the control (Table 5). The application of each of the tested microelements resulted in a significant increase in the number of productive tillers per plant compared to the control, but no significant differences in spike length were observed (Table 5).

The longest spikes, over 7 cm, were developed by plants after the application of molybdenum, and they were also characterized by a high number of productive tillers per plant. The results of the experiment indicate a significant impact of the cultivar used on the measured biometric characteristics. The plants of the RGT Planet cultivar were the tallest (average 68.7 cm), developed the longest spikes (over 7 cm), and were characterized by the highest number of productive tillers per plant (3.77) compared to the other two cultivars. There was no significant interaction between fertilization and the cultivar. Plants in the 2020 growing season were 14.0 cm and 4.2 cm higher, respectively, compared to 2019 and 2021. The longest spikes and the highest number of productive tillers per plant were recorded in 2021 (Table 5).

3.2. Yield Components of Barley

The values of the yield components differed significantly depending on the growing season. The highest number of spikes per m^2, grain weight per spike, and TGW were obtained in 2021 (Table 6). In the experiment, the average number of spikes per m^2 was 704. The lowest was recorded in the Baryłka cultivar after Mn application (673), while the highest was in the RGT Planet cultivar after Mo or Zn fertilization (737). The foliar application of each of the applied microelements resulted in a significant increase in the measured parameter compared to the control. The best effect was obtained after the use of Mo or Zn: increases of 4.1% and 5.4%, respectively, were recorded. Significant differences between cultivars were found. RGT Planet had the highest number of spikes per m^2 (720), while Baryłka had the lowest (687) (Table 6).

Grain weight per spike ranged from 0.58 to 0.76 g. The highest values—above 0.70 g—were recorded after the use of all microelements tested in the RGT Planet cultivar, but the differences were not statistically significant. Compared to Baryłka and KWS Irina cultivars, RGT Planet was characterized by a 12% higher grain weight per spike and produced more grains per spike. The foliar application of each of the tested microelements significantly increased grain weight per spike compared to the control, regardless of the cultivar.

An interaction between fertilization and the cultivar in the number of grains per spike was demonstrated. The highest values were recorded in the RGT Planet cultivar after the application of Cu, Mn, or Zn. Regardless of the cultivars, plants produced more grains per spike after the application of Mn and Zn (18.1 and 18.0) than Cu and Mo, but these differences were not statistically significant.

Table 5. Biometric characteristics of plants depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Plant Height (cm)	Spike Length (cm)	Number of Productive Tillers per Plant
Baryłka	control	63.5 ± 3.2 [a–e]	6.73 ± 0.36 [a]	2.94 ± 0.31 [a]
	Cu	60.1 ± 9.7 [a–c]	6.66 ± 0.46 [a]	3.04 ± 0.42 [a]
	Mn	58.7 ± 10.5 [ab]	7.01 ± 1.31 [a]	3.57 ± 0.62 [a]
	Mo	60.5 ± 9.9 [a–d]	6.65 ± 0.35 [a]	3.51 ± 0.72 [a]
	Zn	59.1 ± 8.9 [ab]	6.59 ± 0.36 [a]	3.36 ± 0.51 [a]
KWS Irina	control	64.5 ± 7.6 [a–e]	6.83 ± 0.37 [a]	2.78 ± 0.26 [a]
	Cu	59.2 ± 7.1 [ab]	6.78 ± 0.62 [a]	3.50 ± 0.52 [a]
	Mn	57.1 ± 6.2 [a]	6.73 ± 0.42 [a]	3.70 ± 0.98 [a]
	Mo	57.2 ± 7.5 [a]	7.04 ± 0.27 [a]	3.92 ± 0.62 [a]
	Zn	57.9 ± 7.4 [a]	6.88 ± 0.39 [a]	3.76 ± 0.73 [a]
RGT Planet	control	70.9 ± 3.7 [e]	7.02 ± 0.48 [a]	3.41 ± 0.62 [a]
	Cu	68.6 ± 5.3 [de]	7.21 ± 0.23 [a]	3.90 ± 0.78 [a]
	Mn	67.9 ± 7.1 [c–e]	7.18 ± 0.35 [a]	4.03 ± 0.83 [a]
	Mo	66.3 ± 6.7 [b–e]	7.65 ± 2.03 [a]	3.71 ± 0.91 [a]
	Zn	69.6 ± 6.9 [e]	7.24 ± 0.50 [a]	3.81 ± 0.55 [a]
$HSD_{p < 0.05}$ C × F		n.s. (0.9598)	n.s. (0.6871)	n.s. (0.4410)
Mean	Baryłka	60.4 ± 8.7 [A]	6.73 ± 0.67 [A]	3.28 ± 0.58 [A]
	KWS Irina	59.2 ± 7.4 [A]	6.85 ± 0.43 [A]	3.53 ± 0.76 [B]
	RGT Planet	68.7 ± 6.1 [B]	7.26 ± 0.97 [B]	3.77 ± 0.75 [C]
$HSD_{p < 0.05}$ C		*** (0.0000)	** (0.0049)	*** (0.0004)
Mean	control	66.3 ± 6.0 [B]	6.86 ± 0.42 [A]	3.05 ± 0.50 [A]
	Cu	62.6 ± 8.5 [A]	6.89 ± 0.51 [A]	3.48 ± 0.68 [B]
	Mn	61.2 ± 9.3 [A]	6.97 ± 0.82 [A]	3.71 ± 0.82 [B]
	Mo	61.3 ± 8.8 [A]	7.11 ± 1.24 [A]	3.77 ± 0.76 [B]
	Zn	62.2 ± 9.2 [A]	6.90 ± 0.49 [A]	3.64 ± 0.62 [B]
$HSD_{p < 0.05}$ F		*** (0.0003)	n.s. (0.5224)	*** (0.0009)
Year (Y)	2019	54.8 ± 7.8 [A]	6.87 ± 0.36 [A]	3.13 ± 0.42 [A]
	2020	68.8 ± 6.3 [C]	6.72 ± 0.70 [A]	3.56 ± 0.73 [B]
	2021	64.6 ± 4.2 [B]	7.25 ± 0.98 [B]	3.90 ± 0.76 [C]
$HSD_{p < 0.05}$ Y		*** (0.0000)	*** (0.0002)	*** (0.0000)
Mean		62.7 ± 8.6	6.95 ± 0.76	3.53 ± 0.73

*** and ** indicate significant differences at $p < 0.001$ and $p < 0.01$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–e and A–C) are statistically different.

The average TGW of barley was 49.3 g. The highest values (above 50 g) were recorded in the RGT Planet cultivar after the foliar application of Mn and Zn. For the KWS Irina cultivar, fertilization with these microelements had the opposite effect. Decreases in TGW of 0.4 and 0.5 g, respectively, were observed. Baryłka and RGT Planet had 0.7 g higher TGW compared to KWS Irina. Regardless of the cultivar, the foliar application of each of the microelements tested resulted in an increase in TGW compared to the control, and the highest value was obtained in plants treated with Mn or Mo (49.5 g) (Table 6).

Table 6. Characteristics of the yield components depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Number of Spikes per m^2	Grain Weight per Spike (g)	Number of Grains per Spike	TGW (g)
Baryłka	Control	679 ± 58 ^{a}	0.68 ± 0.11 ^{a}	18.0 ± 1.2 ^{ab}	49.0 ± 1.8 ^{ab}
	Cu	678 ± 38 ^{a}	0.68 ± 0.18 ^{a}	16.8 ± 2.9 ^{ab}	49.6 ± 2.0 ^{bc}
	Mn	673 ± 61 ^{a}	0.67 ± 0.15 ^{a}	17.7 ± 1.5 ^{ab}	49.5 ± 1.4 ^{b}
	Mo	694 ± 75 ^{a}	0.64 ± 0.12 ^{a}	17.3 ± 1.4 ^{ab}	49.8 ± 2.1 ^{bc}
	Zn	713 ± 97 ^{a}	0.65 ± 0.11 ^{a}	17.3 ± 1.2 ^{ab}	49.5 ± 1.3 ^{b}
KWS Irina	Control	686 ± 76 ^{a}	0.58 ± 0.06 ^{a}	15.8 ± 2.3 ^{a}	48.6 ± 1.6 ^{b}
	Cu	688 ± 64 ^{a}	0.67 ± 0.20 ^{a}	17.7 ± 1.9 ^{ab}	49.8 ± 1.6 ^{bc}
	Mn	719 ± 56 ^{a}	0.68 ± 0.15 ^{a}	17.9 ± 1.2 ^{ab}	48.2 ± 2.1 ^{ab}
	Mo	711 ± 71 ^{a}	0.68 ± 0.17 ^{a}	18.1 ± 1.6 ^{ab}	49.2 ± 1.6 ^{b}
	Zn	719 ± 70 ^{a}	0.70 ± 0.17 ^{a}	18.0 ± 2.0 ^{ab}	48.1 ± 2.6 ^{a}
RGT Planet	Control	693 ± 52 ^{a}	0.67 ± 0.15 ^{a}	18.0 ± 1.8 ^{ab}	48.9 ± 2.0 ^{ab}
	Cu	722 ± 62 ^{a}	0.76 ± 0.11 ^{a}	18.6 ± 1.0 ^{bc}	48.4 ± 2.4 ^{ab}
	Mn	713 ± 51 ^{a}	0.76 ± 0.16 ^{a}	18.7 ± 1.5 ^{bc}	50.6 ± 1.9 ^{c}
	Mo	737 ± 81 ^{a}	0.73 ± 0.14 ^{a}	18.0 ± 1.3 ^{ab}	49.4 ± 2.9 ^{b}
	Zn	737 ± 89 ^{a}	0.76 ± 0.17 ^{a}	18.6 ± 1.8 ^{bc}	50.4 ± 2.1 ^{c}
HSD$_{p\,<\,0.05}$ C × F		n.s. (0.9748)	n.s. (0.8700)	* (0.0458)	** (0.0048)
Mean	Baryłka	687 ± 68 ^{A}	0.66 ± 0.13 ^{A}	17.4 ± 1.7 ^{A}	49.5 ± 1.7 ^{B}
	KWS Irina	705 ± 67 ^{B}	0.66 ± 0.16 ^{A}	17.5 ± 2.0 ^{A}	48.8 ± 2.0 ^{A}
	RGT Planet	720 ± 68 ^{C}	0.74 ± 0.15 ^{B}	18.4 ± 1.5 ^{B}	49.5 ± 2.4 $_{B}$
HSD$_{p\,<\,0.05}$ C		*** (0.0006)	** (0.0057)	* (0.0145)	* (0.0220)
Mean	Control	686 ± 61 ^{A}	0.64 ± 0.12 ^{A}	17.3 ± 2.1 ^{A}	48.8 ± 1.8 ^{A}
	Cu	696 ± 58 ^{AB}	0.70 ± 0.17 ^{B}	17.7 ± 2.1 ^{A}	49.3 ± 2.1 ^{AB}
	Mn	701 ± 58 $^{A–C}$	0.70 ± 0.16 ^{B}	18.1 ± 1.4 ^{A}	49.5 ± 2.0 ^{B}
	Mo	714 ± 76 ^{BC}	0.68 ± 0.14 ^{AB}	17.8 ± 1.4 ^{A}	49.5 ± 2.2 ^{B}
	Zn	723 ± 84 ^{C}	0.70 ± 0.16 ^{B}	18.0 ± 1.7 ^{A}	49.4 ± 2.2 ^{AB}
HSD$_{p\,<\,0.05}$ F		** (0.0013)	** (0.0049)	n.s. (0.3189)	* (0.0257)
Year (Y)	2019	697 ± 66 ^{B}	0.58 ± 0.07 ^{A}	18.4 ± 1.3 ^{B}	49.5 ± 1.7 ^{B}
	2020	648 ± 29 ^{A}	0.62 ± 0.07 ^{B}	16.6 ± 1.1 ^{A}	47.8 ± 2.0 ^{A}
	2021	767 ± 43 ^{C}	0.86 ± 0.12 ^{C}	18.3 ± 2.2 ^{B}	50.5 ± 1.5 ^{C}
HSD$_{p\,<\,0.05}$ Y		*** (0.0000)	*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean		704 ± 69	0.69 ± 0.15	17.8 ± 1.8	49.3 ± 2.1

***, **, and * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–c and A–C) are statistically different.

3.3. Grain Yield, Harvest Index, and Uniformity

In the conducted research, the average GY was 5.60 t·ha^{-1}. The Baryłka cultivar had the highest yield after the application of zinc (5.52 t·ha^{-1}), KWS Irina after the application of Mn (5.87 t·ha^{-1}), and RGT Planet after the application of Mo (6.05 t·ha^{-1}). Regardless of the cultivar, the foliar application of each of the microelements tested resulted in a significant increase in GY compared to the control. The highest GY (above 5.70 t·ha^{-1}) was obtained after the application of Mo and Zn. RGT Planet achieved higher yields of 0.42 t·ha^{-1} and 0.22 t·ha^{-1} compared to Baryłka and KWS Irina cultivars.

Analyzing the value of HI, no significant interactions were found between the cultivar and foliar fertilization with microelements. Only a slight increase in HI was observed in the RGT Planet cultivar after the application of Cu or Mn (0.54) (Table 7). The KWS Irina and RGT Planet cultivars (regardless of foliar fertilization) were characterized by a significantly higher HI compared to Baryłka. The foliar application of each of the microelements tested resulted in a significant increase in HI of 8.3% compared to the control.

Table 7. Values of grain yield, uniformity, and harvest index depending on experimental factors (means in 2019–2021).

Cultivar (C)	Fertilization (F)	Grain Yield (GY) (t·ha^{-1})	Harvest Index (HI)	Uniformity (%)
Baryłka	Control	5.16 ± 0.97 ^{a}	0.49 ± 0.05 ^{ab}	92.7 ± 2.4 ^{a}
	Cu	5.45 ± 0.64 ^{ab}	0.51 ± 0.04 ^{ab}	91.0 ± 4.6 ^{a}
	Mn	5.31 ± 0.86 ^{ab}	0.53 ± 0.02 ^{b}	93.0 ± 4.4 ^{a}
	Mo	5.50 ± 0.80 ^{ab}	0.51 ± 0.04 ^{ab}	92.1 ± 3.7 ^{a}
	Zn	5.52 ± 0.95 ^{ab}	0.52 ± 0.04 ^{b}	93.5 ± 2.9 ^{a}
KWS Irina	Control	5.12 ± 0.90 ^{a}	0.45 ± 0.06 ^{a}	90.8 ± 5.9 ^{a}
	Cu	5.53 ± 0.66 ^{ab}	0.51 ± 0.03 ^{ab}	92.8 ± 3.6 ^{a}
	Mn	5.87 ± 0.57 ^{d}	0.50 ± 0.03 ^{ab}	90.4 ± 5.7 ^{a}
	Mo	5.68 ± 0.94 ^{b}	0.51 ± 0.05 ^{ab}	91.1 ± 5.5 ^{a}
	Zn	5.76 ± 0.90 ^{c}	0.51 ± 0.03 ^{ab}	90.8 ± 5.6 ^{a}
RGT Planet	Control	5.61 ± 0.62 ^{b}	0.50 ± 0.05 ^{ab}	93.0 ± 4.1 ^{a}
	Cu	5.81 ± 0.68 ^{cd}	0.54 ± 0.04 ^{b}	91.2 ± 4.5 ^{a}
	Mn	5.76 ± 0.90 ^{c}	0.54 ± 0.02 ^{b}	93.0 ± 4.7 ^{a}
	Mo	6.05 ± 0.92 ^{e}	0.53 ± 0.04 ^{b}	93.2 ± 4.1 ^{a}
	Zn	5.85 ± 1.03 ^{cd}	0.52 ± 0.03 ^{b}	93.2 ± 4.3 ^{a}
HSD$_{p<0.05}$ CxF		** (0.0096)	n.s. (0.6146)	n.s. (0.2931)
Mean	Baryłka	5.39 ± 0.83 ^{A}	0.51 ± 0.04 ^{B}	92.5 ± 3.7 ^{B}
	KWS Irina	5.59 ± 0.82 ^{B}	0.50 ± 0.05 ^{A}	91.2 ± 5.2 ^{A}
	RGT Planet	5.81 ± 0.78 ^{C}	0.53 ± 0.04 ^{B}	92.7 ± 4.3 ^{B}
HSD$_{p<0.05}$ C		*** (0.0000)	** (0.0020)	* (0.0291)
Mean	Control	5.30 ± 0.85 ^{A}	0.48 ± 0.05 ^{A}	92.2 ± 4.4 ^{A}
	Cu	5.59 ± 0.66 ^{B}	0.52 ± 0.04 ^{B}	91.7 ± 4.2 ^{A}
	Mn	5.65 ± 0.73 ^{B}	0.52 ± 0.03 ^{B}	92.2 ± 5.0 ^{A}
	Mo	5.74 ± 0.89 ^{B}	0.52 ± 0.04 ^{B}	92.1 ± 4.5 ^{A}
	Zn	5.71 ± 0.95 ^{B}	0.52 ± 0.03 ^{B}	92.5 ± 4.4 ^{A}
HSD$_{p<0.05}$ F		*** (0.0000)	*** (0.0000)	n.s. (0.7156)
Year (Y)	2019	5.39 ± 0.75 ^{B}	0.50 ± 0.04 ^{A}	91.9 ± 2.7 ^{B}
	2020	4.94 ± 0.35 ^{A}	0.50 ± 0.03 ^{A}	87.8 ± 3.3 ^{A}
	2021	6.47 ± 0.36 ^{C}	0.53 ± 0.05 ^{B}	96.8 ± 1.0 ^{C}
HSD$_{p<0.05}$ Y		*** (0.0000)	*** (0.0000)	*** (0.0000)
Mean		5.60 ± 0.83	0.51 ± 0.04	92.1 ± 5.0

***, **, and * indicate significant differences at $p < 0.001$, $p < 0.01$, and $p < 0.05$; n.s.—non-significant, according to Tukey's honestly significant difference test (HSD). The mean values with different letters (a–e and A–C) are statistically different.

The average uniformity of barley grain was 92.1%. The statistical analysis performed did not show significant interactions between fertilization and the cultivar. However, differences were found between the barley cultivars tested. Significantly higher uniformity was recorded in Baryłka and RGT Planet cultivars compared to KWS Irina (Table 7).

In the three-year field research, the highest GY, HI, and uniformity were obtained in 2021. In this year, 1.53 t·ha^{-1} and 1.08 t·ha^{-1} more grain was obtained compared to 2019 and 2020, respectively, and the HI index was 0.03 higher. In 2020, the average uniformity was 87.3%, while in 2021, it was 9.5% higher (Table 7).

3.4. Correlation Coefficient Analysis

The analysis of the correlation coefficients showed a very high positive relationship between GY and the number of spikes per m^{-2} (0.88). A high correlation was observed between GY and grain weight per spike (0.66), TGW (0.51), and uniformity (0.65). A high correlation was also noted between uniformity and the number of spikes per m^{-2} (0.60), grain weight per spike (0.56), and TGW (0.68). HI was highly correlated with grain weight per spike (0.55). A high correlation was also observed between the number of grains per spike and grain weight per spike (0.51) (Table 8).

Table 8. Correlation coefficients (r) between the analyzed parameters.

Parameters	Plant Height	Spike Length	Number of Productive Tillers per Plant	Number of Spikes per m^{-2}	Grain Weight per Spike	Number of Grains per Spike	TGW	GY	HI	Uniformity
Plant height	1.00									
Spike length	0.13	1.00								
Number of productive tillers per plant	−0.08	0.06	1.00							
Number of spikes per m^{-2}	0.00	0.22	0.06	1.00						
Grain weight per spike	0.35	0.38	−0.27	0.53	1.00					
Number of grains per spike	−0.09	0.21	0.04	0.25	0.51	1.00				
TGW	−0.05	0.24	0.00	0.44	0.37	0.32	1.00			
GY	0.08	0.27	0.01	0.88	0.66	0.30	0.51	1.00		
HI	0.07	0.17	0.08	0.33	0.55	0.49	0.33	0.39	1.00	
Uniformity	−0.01	0.31	−0.19	0.60	0.56	0.35	0.68	0.65	0.33	1.00

$|r| = 1$ full correlation
$0.9 < |r| < 1.0$ almost full correlation
$0.7 < |r| \leq 0.9$ very high correlation
$0.5 < |r| \leq 0.7$ high correlation
$0.3 < |r| \leq 0.5$ medium correlation
$0.1 < |r| \leq 0.3$ weak correlation
$0.0 < |r| \leq 0.1$ slight correlation
$0.0 < |r| \leq -0.1$ slight correlation
$-0.1 < |r| \leq -0.3$ weak correlation
$-0.3 < |r| \leq -0.5$ medium correlation
$-0.5 < |r| \leq -0.7$ high correlation
$-0.7 < |r| \leq -0.9$ very high correlation
$-0.9 < |r| < -1.0$ almost full correlation
$|r| = 1$ full correlation

4. Discussion

4.1. Influence of Weather Conditions

Climate and soil conditions are among the main factors influencing the growth and yield of crops. Morphological features and yield are also determined by the plant genotype, and the appropriate water resource is the basic factor determining the effectiveness of agricultural crops, including cereals [50–52]. Environmental conditions influence the development of features such as plant height, productive tillers, spike length, and TGW [53–55]. For all major field crops, yield components are produced during the entire crop cycle, from emergence to full maturity [56]. In our study, we noted significant differences in plant yield depending on the year of the field experiment. In three years of research, the best results for yield components were obtained in 2021. In this growing season, the plants had the longest spikes and the highest number of productive tillers. In addition, they developed the most spikes per m^2 and were characterized by the highest grain weight per spike, the highest TGW, and the highest GY. The weather during the barley growing season in 2021 was favorable. April, the month of seed germination and plant emergence, according to the hydrothermal coefficient, was an extremely humid month (Table 4). This resulted in the rapid and uniform emergence of plants. High humidity also had a positive effect on the proper development of plants in May and June. The lowest grain yield was obtained in 2020. In this year, April was a dry month, which negatively affected plant growth. According to Szempliński et al. [57], spring barley yields are most influenced by rainfall in the period from sowing to tillering.

Spring barley in the initial stages of development is highly sensitive to low temperatures. The optimal temperature for the crop during emergence is 5–7 °C and increases to about 8 °C in the leafing and heading phases. This temperature favors the productive tillering of barley plants [57]. In our own research, the average daily temperature in April 2021 was the most beneficial for spring barley (Figure 1).

According to the hydrothermal coefficient, May 2021 was a month with optimal temperature and humidity, while in 2019 and 2020, it was characterized by extremely high humidity (Table 4). Weather factors are particularly important during the shooting and heading periods due to the high sensitivity of barley to water deficiency in these phases, when the most important numerical and physiological components of the yield are determined [58–60]. In these development phases, the favorable conditions are a temperature from 17 to 19 °C and moderate rainfall, according to Pecio [61]. According to Szempliński et al. [57], the thermal optimum in the shooting phase of the barley stalk is 12–15 °C and is lower than that most often occurring in nature, and the optimal rainfall is 19–23 mm/10 days. Spring barley reaches these phases in the second half of May and June. In 2019, June was an extremely dry month, which limited plant heading and grain setting and, as a consequence, could have had a negative impact on the plant yield.

4.2. Influence of Experimental Factors

The main components determining the yield of cereal plants include the number of spikes per unit area, the number of grains per spike, and TGW [60,62–64]. According to Gozdowski and Mądry [65], the number of spikes per 1 m^2 is the yield component that most strongly influences the variability in barley yield. The highest correlation of this parameter with yield was also recorded in our study. In the conducted experiment, the best results were obtained after foliar spraying with Mo or Zn. Molybdenum occurs in the active center of plant enzymes that catalyze key stages of nitrogen, carbon, and sulfur metabolism [66]. Zinc affects the activity of hydrase and carbonic anhydrase, the stabilization of ribosomal fractions, and cytochrome synthesis. This microelement activates plant enzymes that are involved in carbohydrate metabolism, protein synthesis, and the maintenance of the integrity of cell membranes [67]. The plants sprayed with Mo developed the longest spikes and were characterized by the highest number of productive tillers per plant. The foliar application of Zn resulted in the formation of the highest number of spikes per unit area and grain uniformity and also resulted in the highest yield increase. Similarly, in the study by Moghdam et al. [68], who carried out the foliar application of Zn, B, and Cu to two wheat cultivars, it was shown that the type of element had a significant impact on productive tillers, the spike density, the harvest index, and grain yield but had no effect on TGW. After the use of Zn, a higher increase in value was observed compared to Cu. Differences were found between the tested barley cultivars. Similarly, in our experiment, after the application of Zn, a higher number of spikes per m^2 and grain yield were recorded compared to Cu, while the TGW value was similar.

Tillering, i.e., the production of lateral shoots, is an important agronomic attribute that determines the architecture of the canopy and the production of grass grains [69]. In the study by Anjum et al. [70], the use of microelements such as Cu and Zn had a positive effect on the number of productive tillers per plant and spike length. In the study by Noreen et al. [71], a significant increase in the spike length was demonstrated in barley as a result of the foliar application of Zn compared to the control. In the conducted research, the application of both Cu and Zn did not significantly increase the spike length compared to the control, but it significantly influenced the number of productive tillers per plant. Both Cu and Zn increased the measured parameter, and better results were obtained after the use of Zn. In our experiment, the foliar application of each microelement resulted in a reduction in plant height. These results are different from reports from other researchers who showed that spraying microelements can increase the barley plant height [70,72]. The conducted research showed that each of the tested cultivars responded to the applied foliar fertilization by increasing the number of grains per spike and TGW. Significant differences depending on the applied fertilization were observed in the RGT Planet cultivar (an increase in the number of grains per spike after the application of Cu, Mn, and Zn and TGW after the application of Mn and Zn).

Ishaq et al. [73] reported different responses of barley genotypes to Cu and Zn fertilization. Tobiasz-Salach et al. [74] researched the effect of foliar fertilization with Cu and Mn and showed an increase in spike density after the application of microelements, and the obtained effect depended on the cultivar. In our experiment, the RGT Planet cultivar showed the best effect among the tested cultivars. The plants of this cultivar were characterized by the highest values of biometric characteristics and yield components among the tested cultivars. As a rule, the higher the number of spikes per m^2, the smaller the grains. However, the RGT Planet cultivar had the highest number of spikes per m^2 and the highest number and weight of grains per spike. Also, the study by Ishaq et al. [73] conducted on four barley cultivars showed a significant impact of the cultivar on the spike density and TGW. Similarly, studies by other authors showed significant cultivar differences [75,76].

The amount of cereal grain yield is one of the basic factors influencing production efficiency. The application of each of the four tested microelements significantly influenced the increase in GY value. In the study by Liszewski and Błażewicz [77], the influence of Cu, Mn, and Fe on the yield of malting barley was compared. After applying foliar fertilization with microelements, a higher grain yield and improvements in yield components were observed compared to the control. Foliar Mn fertilization applied during malting barley cultivation resulted in statistically significant increases in grain yield of 0.37 $t \cdot ha^{-1}$, and a similar value of 0.35 $t \cdot ha^{-1}$ was obtained in our experiment. The use of micronutrients in the research by Anjum et al. [70] showed that the combined use of Cu and Zn improved the yield and the yield components of barley. In El-Magid's [78] study conducted under saline conditions, an increase in yield was observed due to the foliar application of microelements such as Mn and Zn. A significant increase in grain yield of 19.6% was recorded with Cu foliar spray in a study by Drissi et al. [79]. Barczak et al. [80] reported that Mn and Cu play a significant role in yield formation and cause the greatest increase in barley grain yield among microelements. This relationship was not demonstrated in our own research. The best yield-forming effects were achieved after spraying the plants with Mo or Zn. Similarly, in the study by Boorboori et al. [81], the analysis of the results showed that spraying with a Zn solution significantly increased grain yield. Mo fertilization through foliar sprays can effectively supplement internal molybdenum deficiencies and support the action of molybdoenzymes [82]. For example, the experiment by Mahdavi [83] on barley showed that the foliar application of ammonium molybdate increased the production and development of stems and leaves and, consequently, the productive tillers of barley under drought stress. Five Mo enzymes in plants have been identified to catalyze key reactions in nitrogen assimilation, phytohormone synthesis, sulfite detoxification, and purine degradation [84].

The quality and usefulness of barley grain for brewing purposes are primarily influenced by the genetic characteristics of the cultivars, agronomic practices, and environmental factors. HI is the relationship between the harvested grain and the total biological yield. This parameter is widely used as an indicator of the efficiency of grain assimilation distribution and as a criterion for plant breeding to maximize yields. The value of the indicator is determined by environmental factors and varies between species. In cereals, HI values between 0.3 and 0.6 predominate [85–88]. The HI value can be modified by crop management [89]. Our experience has confirmed that agrotechnical treatments, such as foliar spraying with microelements, influence the increase in HI.

The quality requirements of malting barley are defined more precisely than those of feed and food barley [90,91]. In addition to grain yield, its quality parameters are important, such as protein content, bulk density, TGW, and uniformity [92]. The production of malt requires uniform, large grains. Uniformity is one of the basic parameters determining the usefulness of grain in the brewing industry and should be at least 90%. Plump grains give a higher efficiency of alcohol production, and only these grains are used for malting; therefore, a higher percentage of these grains is the main feature when assessing their usefulness [93–95]. Sharma and Verma [96] reported that features such as bulk density, the proportion of thick and thin grains, and husk content depend mainly on the cultivar and, to a lesser extent, on crop management. Gebeyaw [97] also observed significant differences depending on the cultivar. Similarly, in the conducted research, the value of this feature depended on the cultivar, but no significant increase in value was observed as a result of foliar fertilization with microelements. However, in the study by Dhillon et al. [98], the foliar application of Zn resulted in improved barley uniformity. A decrease in uniformity is caused by a situation in which the increase in productive tillering causes the plants to need to feed a larger number of grains. As a result, the content of plump grains is reduced [99,100]. In our study, we also noted a negative correlation between these parameters. In the experiment of Vahamidis et al. [101], with a decrease in grain yield, a decrease in the share of plump grains was observed. In this study, the potential of grains and spikes had a negative effect on both the grain yield and grain size.

5. Conclusions

This research assessed the impact of the foliar application of micronutrient fertilizers on the components and yield of spring barley brewing forms. The results confirmed the research hypothesis that foliar spraying with fertilizers containing microelements has a positive effect on the yield components and causes an increase in grain yield. Significant differences between cultivars were observed. The analysis showed that the foliar application of fertilizers containing elements such as Cu, Mn, Mo, or Zn in barley cultivation is justified in order to maximize the quantity and quality of the crop. Based on the conducted research, the use of foliar micronutrient fertilizers in malting barley cultivation can be recommended. The application of the fertilizers to the above-ground organs of plants did not interfere with the soil or the effective use of nutrients. This is an important economic and environmental aspect. It is important to expand the research on these issues, which will allow us to optimize spring barley production and increase grain production efficiency for the brewing industry.

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