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Effect of Habitat and Foliar Fertilization with K, Zn and Mn on Winter Wheat Grain and Baking Qualities

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Abstract: Cereal monoculture causes a series of unfavorable changes in field habitat, for example a decrease in technological quality and yield. This system can lead to a shortage of microelements in the diet of poor communities. Moreover, breeding of highly productive plants caused a significant "dilution effect" of the necessary nutrients, such as Zn and Fe. The aim of this work was to determine the effect of two strategies: crop rotation (after rapeseed and many years of monoculture of *Galega orientalis* Lam.) and foliar fertilization with microelements on the yield, yield elements, physical quality, and farinograph characteristics of winter wheat grain and flour. Results showed that pre-crop preparation and cultivation year have the highest effect on yield, yield components, and qualitative and farinographic characteristics of winter wheat. Foliar additional feeding favorably affected the yield and its components, although the particular fertilization treatment did not significantly increase the yield. Grain quality, its physical characteristics and the rheological parameters of flour were strongly modified by habitat conditions, including weather conditions. Dough obtained from wheat grown after galega showed significantly higher water absorption and prolonged consistency.

Keywords: winter wheat; foliar fertilization; pre-crop; grain quality

1. Introduction

Of all the cereals, common wheat (*Triticum aestivum ssp. vulgare*) has the greatest economic significance [1]; it is the basis of human nutrition. About 60% of wheat production is used for food and the concentration of macro- and microelements in the grain is, therefore, of great importance. In developing countries, it contributes to the edible dry matter and daily net intake of calorie consumption by 28% and 60%, respectively (DNB bank < 12 055 USD) [2,3].

The proportion of cereals in the sowing structure in Poland amounts to 72.6% of the total sowing area. Among cereals, wheat growth dominates at 28.6%. In 2016, the wheat sowing area in Poland reached almost 2.1 million ha, including winter wheat with 1.4 million ha (66.1%) and spring wheat with over 704 thousand ha (33.9%) [4].

Cereal monoculture causes a series of unfavorable changes in the field habitat, such as a decrease in technological quality and yield [5]. This system intensifies the problem of shortages in microelements in the diets of poor communities, which encourages mineral malnutrition [6]. Moreover, breeding of highly productive plants has caused a significant 'dilution effect' of the necessary nutrients, such as Zn and Fe [7,8]. Scientists state that contemporary races of cereals have high productivity but their respective wild types contain two to three times more Zn [9]. Wheat, by contrast, has a naturally low

Zn content. Its consumption in rural areas will probably increase to over 70%, which could lead to an increase in the micronutrient shortage in communities with poor resources [10]. Cereals provide up to 52% of the daily requirement for Zn. Biofortification is a process of plant growth that generates high microelement content through traditional breeding or modern biotechnology. It has been stated that Zn concentration in intensively cultivated soils oscillates between 20 and 35 mg kg^{-1}, and may be significantly below that level when wheat is grown in soils poor in zinc [11,12]. In the case of wheat grain, Zn bioavailability reaches about 25% of that amount, which is related to the presence of anti-nutritional factors, such as phitynians and the lack of promoter substances in the grain [13].

Approximately 30% of the population in developing countries, and about 10% of Americans and Canadians, suffer from Zn shortages [14]. It is estimated that 17.3% of the entire world population is at risk of inadequate Zn consumption, and Zn shortage leads to an estimated annual death rate of 433,000 children under the age of 5 [15]. It was recently found that in Great Britain, Zn consumption in about a quarter of teenagers is lower than the Lower Reference Nutrient Intake (LRNI).

There are numerous strategies for improving the intake of micronutrients with plant-based diets and bolstering the condition of plant nourishment in order for microelements to reach food, such as rice diversification, mineral supplementation, enrichment after harvest and bio-diversification [16]. Plant breeding (for example genetic biofortification) and Zn fertilizer application (for example agronomic biofortification) are two important agricultural tools for improving Zn concentration in grains [12]. Agronomic biofortification is obtained through microelement application into the soil and/or directly onto plant leaves [17]. Contrary to genetic engineering, agronomic biofortification is potentially more sustainable, more economical and easier to introduce than other strategies [18,19]. Foliar application of nutrients is an important crop management strategy in order to maximize the yield and microelement concentration in the edible parts. Several studies demonstrated that foliar microelement application, including Zn, was effective in increasing the microelement concentration in wheat grain [20–22]; for example, the combination of nitrogen fertilizer with Zn added into the soil or onto the leaves increased both the yield and the nutrient uptake [7,23]. In wheat, Zn translocation from flakes to grain is also made easier by metal chelating agents, such as 2-deoxymugineic acid (DMA) [8]. With a high N index, 80% of Zn goes to the grain, which underscores the role of N in supporting the movement of Zn in wheat [24]. Erenoglu [9] demonstrated that biofortification of food cultivation must take into account the key role of nitrogen in Zn uptake and accumulation. The role of nitrogen in facilitating the uptake, transportation, translocation and deposit of microelements, in particular of Zn in cereal grain, has been thoroughly studied [25].

The yield and quality if wheat grain depend on the characteristics of the cultivar, applied agrotechnics and environmental factors [1,26]. The cultivar also dictates wheat's technological value. Important characteristics of quality assessment are: protein content, amount of gluten, Zeleny sedimentation value and falling number. In addition to these, the indication of winter wheat rheological properties is also important.

The yield and the technological and nutritional value of the grain yield are determined by meeting plant nutritional needs through supplying proper minerals during fertilization [27]. The method of application and the applied dose are both of great importance. One such method is foliar plant fertilization with microelements at the moment of critical demand for nutrients [28]. The treatment is recommended at the straw-shooting stage because this is when intensive cell divisions occur. In the additional feeding of cereals, particular attention is paid to Mn, Cu and Zn, due to their active role in many physiological processes [27]. Positive aspects of foliar plant fertilization are its high production efficiency [29] and an increase in the quality of technological parameters [1].

The optimization of grain yield and winter wheat quality depends not only on proper fertilization, but also on crop rotation. Damage by fungus infection, deterioration of soil structure and a negative effect on the water and air regime in the soil are the main causes of reduction in grain yield in improperly composed crop rotation. Proper crop rotation uses particular abilities of certain plant species in order to favorably affect the physical, chemical and biological properties of soils [30]. Wheat is sensitive to pre-crop choice; a lower yield of wheat is grown in monoculture or after an unsuitable pre-crop. This leads to a reduction in particular yield elements as a result of: nutrient exhaustion, increase in infestation, intensification of pest and fungus infection, changes in soil microorganism activity in the soil structure and release of phytotoxic substances from the roots and harvest residue [31,32]. Rapeseed and legumes are considered to be good pre-crops for winter wheat [33,34]. The yield of wheat grown after those species reaches 92% of the value reported for the best pre-crop [32]. Galega long term cropping, i.e., 12-year monoculture, as a result of the lack of specialized agrophages, is characterized by high durability in habitat. During growth and development, it fixes atmospheric nitrogen very effectively. It is a plant that meets the demands of biological soil reclaim very well [35]. The decomposition of rapeseed harvest residue has several benefits, including the release of glucosinolates into the soil, which results in an increase in the amount of microorganisms antagonistic to cereal fungus pathogens [36].

The aim of this work was to determine the effect of crop rotation after rapeseed and many-years' monoculture of *Galega orientalis* Lam. and foliar fertilization with microelements on the yield, yield elements, physical quality and farinograph characteristics of winter wheat grain and flour. The working hypothesis assumed that the pre-crop of winter wheat (galega vs. oilseed rape) and foliar supplementation of microelements have attributes that affect the productivity and baking quality of wheat grain.

2. Materials and Methods

2.1. Experiment Location

The field experiments were set up at the Experimental Station of the Faculty of Agriculture and Biotechnology at the UTP University of Science and Technology in Bydgoszcz, Poland. The station is located in Mochle, Sicienko municipality (53°12′ N, 18°01′ E), Bydgoszcz district, Kuyavian-Pomeranian Voivodeship. The study was carried out in the growth seasons of 2015–2016 and 2016–2017.

2.2. Study Factors

The study involved two strict field experiments (H1, H2) set up in a split-block design in four replications. The size of the plots for sowing was 1.20 m (width) by 16.6 m (length), and consistet of eight rows with a 15-cm spacing. The subject of the study was winter wheat (*Triticum aestivum ssp. vulgare)*, cultivar "Arkadia", in the growth seasons of 2015–2016 and 2016–2017.

In the experiment, the effects of two factors were studied:

H—Stand defined as pre-crop for winter wheat and soil conditions (Table 1):

Table 1. The content of nutrients available in the soil before sowing winter wheat in the study years (mg 1000g $^{-1}$ of soil) in two habitats.

Compound	H1		H2
	2015	2016	2015
$P_{available}$	95.9	135.4	273.0
$K_{available}$	167.6	179.2	336.6
$Mg_{replaceable}$	54.5	57.2	66.2

H1: stand after winter rapeseed, H2: Stand after a 12-year-long Galega orientalis Lam. monoculture.

H1. Stand after winter rapeseed. Soil class III a, very good wheat or rye complex, soil pH 6.8 in KCl.;

H2. Stand after a 12-year-long *Galega orientalis* Lam. monoculture. Soil class V, poor rye complex, soil pH 5.0 in KCl.

F—Foliar fertilization in wheat:

F0. Control plot with no foliar fertilization;

F1. Mix of granules comprising of 2 kg ha^{-1};

F2. Mix of granules comprising of 1.5 kg ha^{-1} + Mn 0.5 kg ha^{-1} and Zn 0.5 kg ha^{-1};

F3. Mix of granules comprising of 1.5 kg ha^{-1} + Mn 0.5 kg ha^{-1} and Zn 0.5 kg ha^{-1} + Mn 1.0 kg ha^{-1} and Zn 1.0 kg ha^{-1}.

Composition of foliar fertilizers (in weight %):

Mix of granules: total N 4% (NH_4 4%), P_2O_5 12%, K_2O 38%. (ADOB®NPK Foliar 4-12-38- fertilizer for foliar application), dose recommended by the producer is 2–3 kg/ha in split doses. Compound crystal fertilizer with an increased potassium content for the supplementation of in-soil fertilization, especially in the case of potassium (K) deficit and in stressful conditions.

Mn: total N 6.5% (NO_3 6.5%), MgO 2%, Mn 10.1% (Mn ADOB®2.0 Mn- liquid foliar fertilizer), total dose recommended by the producer is 1–1.5 kg ha^{-1}. It supplies easily assimilable manganese and contributes to increased plant winter hardiness, undisturbed plant growth, and efficient chlorophyll production.

Zn: 10% totally chelated in IDHA = iminodisuccinic acid, (ADOB®2.0 Zn IDHA- liquid foliar fertilizer), dose recommended by the producer is 1 kg ha^{-1}.

2.3. Agrotechnical and Soil Conditions

Before winter wheat was sown, soil preparation was carried out according to the recommendations by the Institute of Soil Science and Plant Cultivation–State Research Institute (IUNG-PIB) in Puławy. After a rapeseed harvest, the ground was tilled; then three weeks before sowing the soil was ploughed to a depth of 25 cm; subsequently, the ground was worked with a tiller and a harrow. Soil cultivation after the 12-year-long Galega orientalis Lam. monoculture consisted of deep ploughing (30 cm) with a skimmer in August, and then three weeks before the wheat was sown, ploughing at the depth of 25 cm and then tilling the ground with a tiller and a harrow). Before soil fertilization, soil samples were collected in order to evaluate the content of the assimilable forms of macroelements. Samples were collected using the Egner's rod from the depth of 0–20 cm.

In the autumn, during pre-sowing soil cultivation, 50 kg $P_2O_5 \cdot ha^{-1}$ and 80 kg $K_2O \cdot ha^{-1}$ were applied in one dose. Nitrogen fertilization was applied in three doses. The first one, in the amount of 50 kg $N \cdot ha^{-1}$, was applied in the spring at the onset of growth (BBCH 23), the second one, 30 kg $N \cdot ha^{-1}$, at the third node stage (BBCH 33) (BBCH-development phase of grain) and the third dose, 30 kg $N \cdot ha^{-1}$, at the flag leaf sheath swelling stage (BBCH 43).

Seed sowing was carried out with a OYORD seed drilling device (Wintersteiger AG, 4910 Ried, Austria), with a row spacing of 15 cm. Qualified sowing material was used with a germination capacity of over 95% and a purity of over 98%. Sowing density reached 550 grains per 1 m^2. Sowing material was treated with the seed dressing Scenic 080 + Perfektseed. The sowing date in the first study year was 01.10.2015, and in the second study year 29.09.2016.

As weed control, an herbicide mixture was applied: Helmstar 75 WG (methyl tribenuron) 40 g/ha + Apyros 75 WG (sulfosulfuron) 15 g ha^{-1} with adjuvant Atpolan 80 EC 1.5 l ha^{-1}. Application was carried out with a field sprayer at BBCH 32.

When diseases occurred, relevant plant protection products were applied according to the recommendations of the Institute of Plant Protection (IOR). Intervention against powdery mildew and leaf spots consisted of plant spraying at the T2 stage with preparation Fandango 200 EC (prothioconazole + fluoxastrobin) at a dose of 1.2 l ha^{-1}.

Foliar sampling was carried out manually two weeks after foliar application (BBCH 49), gathering 20 flag leaves per plot (Table 2). Grain harvest was carried out with a Wintersteiger plot harvester at the stage of full grain ripeness (BBCH 89). In the first year, harvest was carried out on 08.08.2017, and in the second year a week later (15.08.2017) (Table 2).

Table 2. Dates of the experimental characteristics.

Year	Date			
	Sowing	**Foliar Fertilization**	**Foliar Sampling**	**Harvest**
2015/2016	01.10.2015	19.05.2016 03.06.2016	03.06.2016 18.06.2016	08.08.2016 ^{H1} 12.08.2016 ^{H2}
2016/2017	29.09.2016	24.05.2017 10.06.2017	08.06.2017 25.06.2017	15.08.2017 ^{H1} 20.08.2017 ^{H2}

Habitat (H1, H2).

2.4. Meteorological–Standard Measurements from the Measuring Point at the Experimental Station in Mochełek

The topography of the plots is low-lying and the climate of the region is temperate and influenced by both the Atlantic Ocean and the Asian continent. The mean annual temperature is 7.6 °C and the average temperature in January is −2.3 °C; in July it is 18.1 °C (Figure 1). Within this region is an area with one of the lowest precipitation levels in Poland, with less than 500 mm annually (data from 1949 to 2015). The total year sum (mm) was 564 in 2015/2016 and 688.8 in 2016/2017. Total precipitations were very high in June and July 2016, about 50 mm higher than the average (from 1949 to 2015). In turn, August 2017 had a rainfall of 74 mm above average (Figure 2).

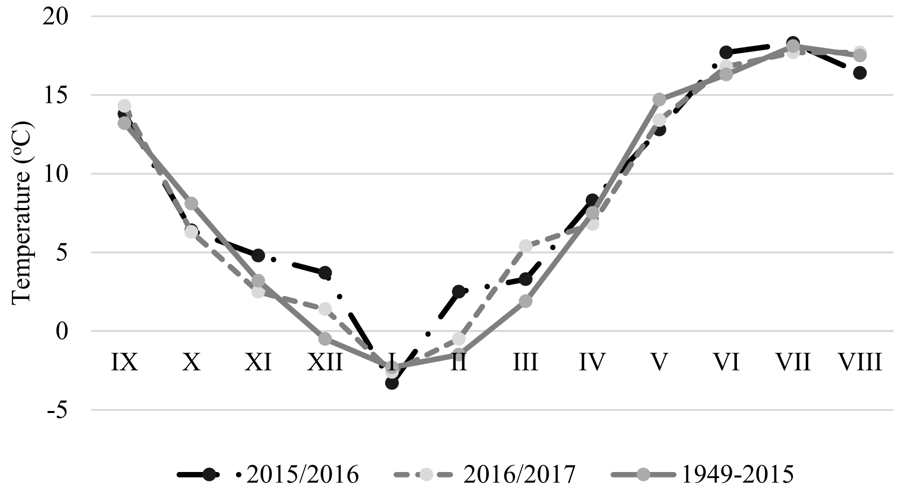

Figure 1. Air temperature (°C) in the years of study and of the multi years.

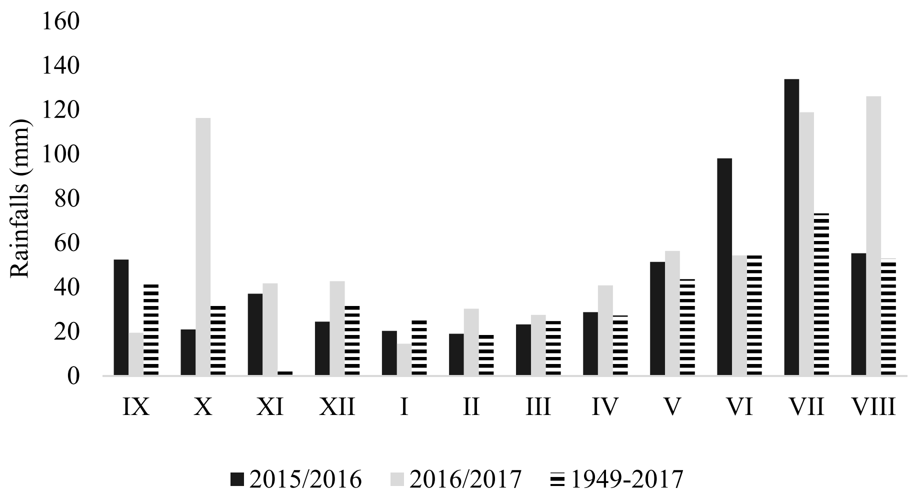

Figure 2. Rainfalls (mm) in the years of study and of the multi years.

2.5. Yield and Yield Elements

The density of ears was measured at BBCH 99 on the sub-plots $1m^{-2}$. Before harvest the ears from the sub-plots were cut in order to determine the ear's length and the number of kernels per ear. The grain yield was measured in kg from 14 m^2 plots and calculated in tons per hectare (Mg 10 000 m^{-2}) adjusted to 12.5% of grain moisture. The numbers of kernels and the thousand kernel weight (TKW) expressed in g was measured from the sampled grain.

2.6. Qualitative Markers in Wheat Grain and Flour

The percentage of N in the grain was determined using the Kjeldahl micro-method, followed by a colorimetric reading using a Buchi B-324 (Büchi Laboratory AG, Flawil, Switzerland). Cereal protein concentration was calculated by multiplying N by 6.25. The following grain parameters were determined: mass of one thousand grains (g) and test weight (kg hL^{-1}). The flour was then evaluated by ICC (Standard Methods of the International Association for Cereal Science and Technology) standard methods: Hagberg–Perten falling number using an SWD-83 camera (Poland) [37], sedimentation rate [38], gluten content (%), gluten weakening (mm) and gluten index (%) [39]. The rheological properties of the dough were also determined: flour water absorption (corrected to 14%), development time (min), dough stability (min) and the degree of softening (FU), using a Brabender farinograph (Duisburg, Germany), according to the standard methods [40]. Analyses were carried out for every combination in two replications.

2.7. Chemical Analysis

The material for the potassium (K) concentration analyses was subjected to mineralization in concentrated sulfuric acid (H_2SO_4) and perchloric acid ($HClO_4$), whilst the material for zinc (Zn) and manganese (Mn) concentration analyses was digested in a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$). An Atomic Absorption Spectrometer (ASA) apparatus (iCE 3000 Series, Thermo Fisher Scientific) was used to determine potassium (K) by means of emulsion flame spectroscopy, and zinc (Zn) and manganese (Mn) by means of absorption flame spectroscopy. The content of available phosphorus (P) and potassium (K) was determined by the Egner–Riehm method [41]. For the determination of the amount of magnesium (Mg) in the soil, extraction was performed using a buffered barium chloride solution at pH = 8.1 [42].

2.8. Statistical Analysis

Results obtained for all of the qualitative characteristics of wheat grain and flour underwent a two-factor analysis of variance in a split-block design after a normality check using the Shapiro–Wilk test: the stability of variance was tested using a Levene's test in the subsequent study years, using a synthesis of the results from two years. Verification of null hypotheses was carried out on the basis of the F test for $p < 0.05$. For the proven effects of the experimental factors in wheat characteristics, testing of the differences between the average plot values was carried out with the use of the HSD *post-hoc* Tukey's test (Tukey's honest significant difference test) at the level of $p < 0.05$.

3. Results

The TKW and falling number were dependent on the winter wheat harvest year ($p < 0.01$). The harvest year and habitat significantly affected protein and gluten content, the Zeleny test, water absorption and stability ($p < 0.01$). Development time depended only on the habitat ($p < 0.01$). The interaction between harvest year × habitat and foliar fertilization significantly affected stability ($p < 0.01$) and gluten index ($p < 0.05$). The interactions of harvest year × habitat, harvest year × foliar fertilization, habitat × foliar fertilization, harvest year × habitat × foliar fertilization and foliar fertilization had no significant effect on the other study factors (Table 3).

Table 3. Significance of the main effects and interactions of the experimental factors in ANOVA.

Characteristic	Y	H	Y * H	F	Y * F	H * F	Y * H * F	V%
TKW (g)	**	ns	ns	ns	ns	ns	ns	2.1
Test Weight (kg hL^{-1})	**	ns	ns	ns	ns	ns	ns	3.6
Grain Fraction >2.2 mm (%)	ns	ns	ns	ns	ns	ns	ns	3.2
Falling Number (s)	**	ns	ns	ns	ns	ns	ns	6.3
Protein Content (%)	**	**	ns	ns	ns	ns	ns	3.4
Gluten Content (%)	**	**	ns	ns	ns	ns	ns	5.9
Gluten Index (%)	ns	ns	*	*	ns	ns	ns	5.3
Zeleny Test (mL)	**	**	ns	ns	ns	ns	ns	4.3
Water Absorption (%)	**	**	ns	ns	ns	ns	ns	4.7
Development Time (min)	ns	**	ns	ns	ns	ns	ns	8.7
Stability (min)	**	**	**	**	ns	ns	ns	7.6
Degree of Softening (FU)	ns	ns	ns	ns	ns	ns	ns	6.6

Significance of the main effects and interactions of the experimental for both habitat (H1, H2). Thousand kernel weight (TKW). Y: years, H: habitat, F: foliar fertilization, ns: non significant, *significant at $p < 0.05$, ** significant at $p < 0.01$.

The physical properties of the grain such as TKW, test weight and grain fraction were not diversified by habitat or foliar fertilization. The values of the above characteristics were similar and assigned to the same homogenous groups. On the other hand, TKW and test weight depended on the harvest year and were significantly higher in the second study year (2017), by 8% and 3%, respectively (Table 4).

Table 4. Physical properties of grain—main effects of the factors.

Factor	Variant	TKW (g)	Test Weight (kg hL^{-1})	Grain Fraction >2.2 mm (%)
Habitat (H)	H1	42.2 a$^{\#}$	77.4 a	98.7 a
	H2	42.3 a	78.9 a	98.6 a
Foliar Fertilization (F)	F0	42.2 a	78.4 a	99.0 a
	F1	42.0 a	78.2 a	98.5 a
	F2	42.3 a	77.8 a	98.5 a
	F3	42.4 a	78.2 a	98.5 a
Year (Y)	2016	40.6 b	76.8 b	97.6 a
	2017	43.9 a	78.9 a	99.7 a
Mean		42.2	78.2	98.6

The same letters indicate a homogenous group according to the HSD Tukey's test at $p < 0.05$ (a, a$^{\#}$, b). Thousand kernel weight (TKW).

Among the studied quality properties of grain and dough, pre-crop type diversified only protein and gluten contents (Table 5). Wheat grown after galega contained significantly more protein and gluten, by 7% and 13%, respectively, than wheat grown after winter rapeseed (Table 5). Applied foliar fertilization determined only the falling number. The highest values were noted in wheat collected from plots fertilized with the mix of granules with the addition of Zn and Mn applied twice (F3), on average by 17% when comparing to the control plots. Grain from wheat collected from the control plots was characterized by the lowest falling number. Significantly higher values of the falling number (by 11%), protein (by 6%), gluten (by 25%) and the Zeleny test (by 90%) were obtained in the second study year. Gluten index was significantly higher in the first study year (by 40%).

Table 5. Quality properties of grain and flour—main effects of the factors.

Factor	Variant	Falling Number (s)	Protein Content (%)	Gluten Content (%)	Gluten Index (%)	Zeleny Test (mL)
Habitat (H)	H1	317 a[#]	12.7 b	29.8 b	82.9 a	24.2
	H2	312 a	13.6 a	33.8 a	86,9 a	27.4
Foliar Fertilization (F)	F0	286 b	12.9 a	31.3 a	83.4 a	26.3
	F1	318 ab	13.4 a	31.6 a	83.8 a	25.0
	F2	319 ab	13.1 a	32.2 a	85.0 a	25.5
	F3	335 a	13.2 a	31.5 a	85.5 a	26.6
Year (Y)	2016	296 b	12.7 b	28,1 b	99.2 a	14.4
	2017	330 a	13.5 a	35.2 a	70.7 b	27.4
Mean		315	13.1	31.7	84.9	25.9

The same letters indicate a homogenous group according to the HSD Tukey's test at $p < 0.05$ (a, a[#], ab, b).

Significantly higher water absorption (by 8%), development time (by 14%) and stability (by 49%) were found in the flour from wheat grown after galega (Table 6). Pre-crop had no significant effect on the degree of softening. Applied foliar fertilization did not determine the farinographic properties of grain and dough. Significantly higher water absorption was characteristic for the flour from wheat collected in the first study year, on average by 51%, in comparison with the second study year. In the second study year, significantly higher values of stability and the degree of softening were found than in the first year, on average by 23% and 18%, respectively.

Table 6. Farinograph properties of grain and flour—main effects of the factors.

Factor	Variant	Water Absorption (%)	Development Time (min)	Stability (min)	Degree of Softening (FU)
Habitat (H)	H1	45.2 b	1.83 a	1.76 b	77.6 a
	H2	48.9 a	2.09 b	2.62 a	79.5 a
Foliar Fertilization (F)	F0	47.4 a	1.88 a	2.20 a	78.6 a
	F1	46.0 a	1.88 a	2.16 a	79.6 a
	F2	46.9 a	2.12 a	2.22 a	78.0 a
	F3	47.5 a	1.98 a	2.18 a	77.8 a
Year (Y)	2016	56.5 a	1.95 a	1.95 b	72.1 b
	2017	37.4 b	1.98 a	2.41 a	85.0 a
Mean		46.9	1.96	2.19	78.6

The same letters indicate a homogenous group according to the HSD Tukey's test at $p < 0.05$ (a, b)

Analyzed study results indicate multiple regression equations between the protein content (y) and gluten content, gluten index, the Zeleny test, water absorption and stability (Table 7). Coefficients of correlation for the particular quality characteristics were high (gluten content, $r = 0.82$, gluten index, $r = -0.50$, the Zeleny test, $r = 0.73$, water absorption, $r = 0.88$, and stability $r = 0.91$). As gluten content increased by one unit, protein content increased by 5.86%. A one-unit increase in gluten index decreased protein content by 12.2%. A one-unit increase of the Zeleny test/sedimentation index caused a 13.4% increase in protein content. An increase in water absorption and stability by one unit resulted in the increase in protein content consecutively by 2.99% and 0.73%.

In both study years, stability of dough from the grain of wheat grown after galega was significantly more favorable, reaching from 2.3% to 2.9% (Figure 3). The gluten index value was significantly higher in flour from wheat grown after galega in the second study year (75%) (Figure 4).

Table 7. Correlation and regression dependency between the protein content (y) and quality characteristics of wheat grain and flour, $n = 16$.

Characteristic	Regression Equation	r	r^2
Gluten Content (%)	Y = −44.0 + 5.86 x	+0.82	0.672
Gluten Index (%)	Y = 245 − 12.2 x	−0.50	0.250
Zeleny Test (mL)	Y = −150 + 13.4 x	+0.73	0.533
Water Absorption (%)	Y = 18.9 + 2.99 x	+0.88	0.744
Stability (min)	Y = −7.22 + 0.73 x	+0.91	0.828

r: multiple correlation coefficient, r^2: determination coefficient, Y: dependent variable.

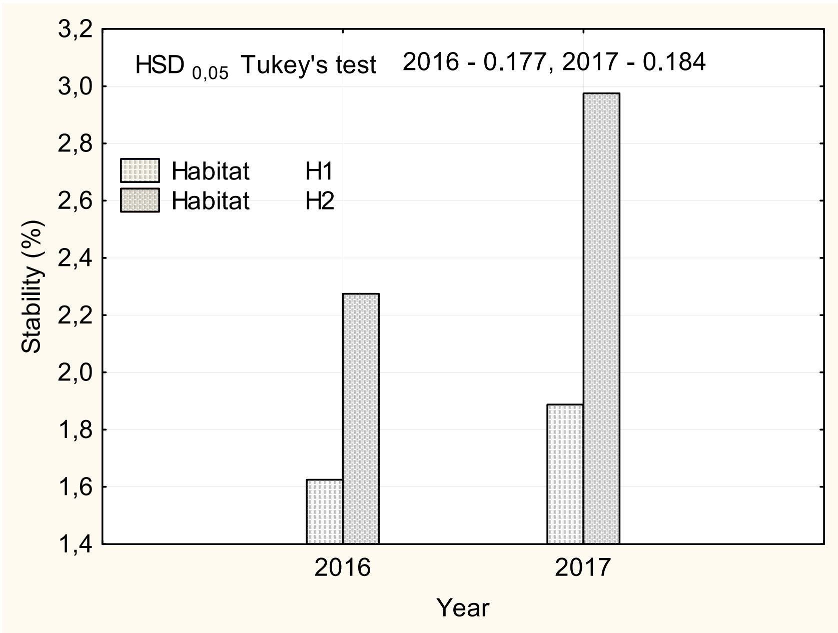

Figure 3. Effect of habitat on stability in 2016 and 2017.

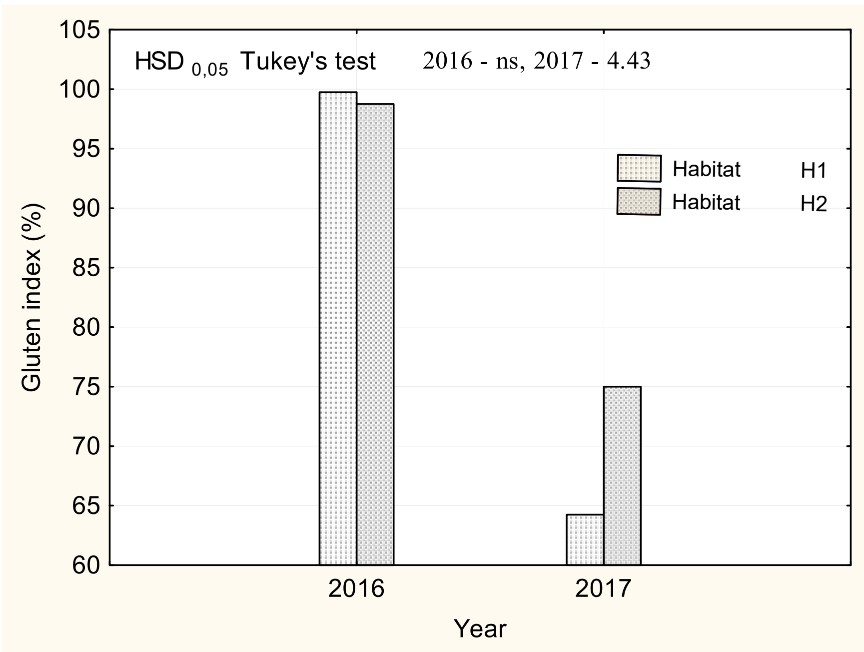

Figure 4. Effect of habitat on gluten index in 2016 and 2017.

Pre-crop type and additional foliar fertilization significantly affected the yield, number of grains per ear, ear length and TKW ($p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively). Study factors did not diversify only the number of ears per m^2. The interaction pre-crop × fertilization significantly affected wheat grain yield and ear length ($p < 0.05$, $p < 0.01$) (Table 8).

Table 8. Wheat yield and its components depending on habitat and foliar fertilization. Mean values ± S_E from 2016–2017.

Habitat (H)	Foliar Fertilization (F)	Number of Ears per m^2	Number of Kernels per Ear	Ear Length (cm)	TKW (g)	Grain (t ha^{-1})
H1	F0	443 ± 20.9	26.6 ± 2.37	6.98 ± 0.45 c	37.9 ± 0.80	4.99 ± 0.11c
	F1	408 ± 22.9	33.3 ± 3.92	8.22 ± 0.26 a	43.3 ± 0.56	5.90 ± 0.10 a
	F2	412 ± 24.9	32.0 ± 3.34	7.81 ± 0.54 ab	44.5 ± 1.31	5.60 ± 0.15 ab
	F3	448 ± 8.4	1.0 ± 3.43	7.17 ± 0.36 bc	44.9 ± 1.43	5.49 ± 0.12 abc
	Mean	428 ± 10.2	30.7 ± 3.79 B	7.54 ± 0.63 B	42.7 ± 0.87A	5.50 ± 0.08 A
H2	F0	424 ± 16.0	31.0 ± 4.41	7.88 ± 0.27 abc	28.0 ± 0.80	3.96 ± 0.10 d
	F1	400 ± 20.5	34.0 ± 5.16	7.98 ± 0.26 abc	33.6 ± 1.44	5.07 ± 0.16 ab
	F2	395 ± 17.0	35.0 ± 3.34	8.17 ± 0.61 ab	34.4 ± 1.29	4.98 ± 0.13 c
	F3	417 ± 10.7	39.9 ± 4.76	8.31 ± 0.54 a	31.0 ± 1.01	5.22 ± 0.10 a
	Mean	409 ± 8.1	35.0 ± 5.41 A	8.06 ± 0.45 A	31.7 ± 0.83 B	4.80 ± 0.11 B
Overall	F0	433 ± 12.9	28.8 ± 4.06 B	7.43 ± 0.59 B	32.9 ± 1.94 B	4.48 ± 0.15 B
	F1	404 ± 14.7	33.6 ± 3.92 AB	8.05 ± 0.30 A	38.5 ± 1.98 A	5.48 ± 0.14 A
	F2	404 ± 14.8	33.5 ± 4.18 AB	7.99 ± 0.57 A	39.4 ± 2.09 A	5.29 ± 0.13 A
	F3	433 ± 7.7	35.4 ± 6.11 A	7.74 ± 0.74 AB	37.9 ± 2.75 A	5.35 ± 0.08 A
	Mean	418 ± 6.6	38.0 ± 1.24	7.80 ± 0.59	37.2 ± 1.15	5.15 ± 0.08
F	Factor H (1; 53) &	2.03	9.45 **	11.7 **	17.9 ***	39.9 ***
	Factor F (3; 53)	1.70	4.12 *	3.56 *	12.7 ***	26.1 ***
	H x F (3; 53)	1.12	1.52	4.72 **	1.52	3.33 *

The same letters indicate a homogenous group according to the HSD Tukey's test at $p < 0.05$, small letters for interaction (a, ab, abc, bc, c, d), big letters for main effects (A, B, AB). TKW: thousand kernels weight, & degrees of freedom, *F significant at $p < 0.05$, ** F significant at $p < 0.01$, *** F significant at $p < 0.001$.

Average winter wheat yield oscillated between 4.80 and 5.50 t · ha^{-1}, depending on the pre-crop (Table 8). Winter rapeseed appeared to be a better pre-crop for winter wheat as, in comparison with growth after galega, it achieved higher grain productivity by about 15% (0.7 t · ha^{-1}). The application of additional foliar fertilization resulted in a significant increase in grain yield, both in growth after winter rapeseed and after galega. The most significant effect of additional foliar fertilization was found in wheat grown after galega. In comparison with the control plot, after the application of the mix of granules with the addition of Zn and Mn on two dates (F3), wheat yield increased on average by 32%. In wheat grown after winter rapeseed, the highest grain yield was obtained after the application of the mix of granules (F1), and it was higher on average by 18% (0.91 t · ha^{-1}) as compared to that collected from the control plots. Winter wheat responded well to the applied foliar fertilization; however, no significant differences were found in yield between the particular fertilization variants (F1, F2, F3). In comparison with the control plot, a considerably higher yield increase was noted after the application of the mix of granules (F1), on average by 22% (1.0 t · ha^{-1}).

Wheat grown after winter rapeseed had a notably higher TKW, on average by 35% (Table 8). In spite of the fact that no statistically significant effect of the interaction pre-crop × fertilization was found, TKW increased substantially under the effect of foliar fertilization. The applied fertilization variants (F1, F2, F3) demonstrated similar effects, although the highest TKW was obtained after the application of the mix of granules with the addition of Zn and Mn (F2), by 20% in comparison with the control plot.

Longer ears were noted in wheat collected from plots after the galega pre-crop, on average by 7% (Table 8). Similarly, in the case of yield, the best effects of the interaction pre-crop × fertilization were noted after the application of the mix of granules (F1) in growth after winter rapeseed and after the mix of granules with the addition of Zn and Mn applied on two dates (F3) in growth after galega. Wheat collected from the above fertilization variants had ears longer by 18% and 5%, respectively. Ear lengths in wheat fertilized with the mix of granules (F1) and the mix of granules, with the addition of Zn and Mn (F2), were similar and did not differ significantly. The longest ears in relation to the control plot were found in wheat fertilized with mix of granules (F1), on average by 8%.

The number of grains per ear was dependent on the pre-crop and was considerably higher in wheat grown after galega, on average by 14% (Table 8). The interaction between the study factors did not significantly influence the number of grains per ear. The highest number of grains was found in wheat fertilized with the mix of granules with added Zn and Mn applied on two dates (F3), higher by 23% on average as compared to the control plot.

The applied agrotechnical factors had no significant effect on the number of ears per area unit (Table 8).

Regardless of the harvest date, the leaves of winter wheat grown after galega or winter rapeseed did not differ significantly in Zn content (Table 9). However, a tendency towards a decrease in the concentration of Zn in leaves collected on the second date was found. All of the fertilization variants (F1, F2, F3) favorably affected Zn concentration in wheat leaves in both studied habitats. Leaves of wheat grown after galega contained significantly more Zn than the leaves of wheat grown after winter rapeseed, by 7% (1.5 mg kg^{-1}) on the first date and 24% (3.2 mg kg^{-1}) on the second date.

Table 9. Zinc (Zn), Manganese (Mn) and Potassium (K) content in wheat leaves and grain depending on the habitat and foliar fertilization, in dry weight. Mean values from 2016–2017.

Organ/Sampling		Foliar Fertilization (F)	Habitat (H)					
			Galega Pre-crop			Rapeseed Pre-crop		
			Zn (ppm)	Mn (ppm)	K (g · kg^{-1})	Zn (ppm)	Mn (ppm)	K (g · kg^{-1})
Leaf	14 DAT I	F0	19.2 c	32.2 d	14.00 b	16.1 b	26.3 b	17.40 c
		F1	22.9 a	46.5 c	17.10 a	19.9 a	34.1 a	18.80 bc
		F2	21.1 b	57.8 b	17.70 a	21.5 a	35.6 a	19.30 b
		F3	22.2 a	61.4 a	18.00 a	22.0 a	35.6 a	22.30 a
		Mean	21.4 A	49.5 A	16.7 B	19.9 B	32.9 B	19.5 A
	14 DAT II	F0	14.5 c	64.0 c	11.60 c	11.8 c	33.0 b	13.10 c
		F1	15.6 b	87.0 b	30.40 a	12.2 c	33.1 b	17.70 b
		F2	17.9 a	86.0 b	20.30 b	13.3b c	36.2 b	19.50 b
		F3	17.0 a	105.9 a	32.70 a	14.9 a	44.7 a	28.10 a
		Mean	16.3 A	85.7 A	23.8 A	13.1 B	36.8 B	19.6 B
Grain		F0	34.3 ab	45.8 c	0.40 b	22.8 b	30.7 b	0.43 b
		F1	33.5 bc	44.1 c	4.30 a	21.6 b	30.1 b	4.28a
		F2	32.9 c	49.1 bc	4.60 a	21.8 b	30.2 b	4.21 a
		F3	35.6 a	55.9 a	4.70 a	35.6 a	55.9 a	4.57 a
		Mean	34.1 A	48.7 A	3.50 A	25.5 B	36.7 B	3.37 A

The same small letters indicate a homogenous group in foliar fertilization according to the HSD Tukey's test at $p < 0.05$ (a, ab, b, bc, c). The same capital letters indicate a homogenous group in the habitat according to the HSD Tukey's test at $p < 0.05$ (A, B)

Furthermore, Mn content in leaves did not differ significantly depending on the harvest date, in both the growth after galega and after winter rapeseed (Table 9). However, a tendency for an increase in Mn concentration on the second harvest date was found. In both habitats, foliar fertilization application increased Mn content in the leaves. The best effects were obtained after the application of the mix of granules with the addition of Zn and Mn applied twice (F3), both in wheat grown after galega and after rapeseed. Similar to the case of Zn, the leaves of wheat grown after galega contained more Mn than the leaves of wheat grown after rapeseed, by 50% (16.6 mg kg^{-1}) on the first date and more than double the amount (48.9 mg kg^{-1}) on the second date.

Leaves of wheat grown after galega contained significantly more K on the second date than the leaves collected on the first date, on average by 42% (7.1 g kg^{-1}) (Table 9). Similarly, in the growth after rapeseed, leaves collected on the second date contained more K, on average by 0.5% (0.1 g kg^{-1}). The fertilization variant of the mix of granules with the addition of Zn and Mn applied twice (F3) proved to be the most favorable in regards to increasing K concentration in the leaves. Leaves of wheat grown after galega and rapeseed collected from variant F3 contained significantly more K. On the second harvest date, the increase was more than double. On the first harvest date, in wheat grown after rapeseed, there was significantly more K than in wheat grown after galega, on average by 17% (2.8 g kg^{-1}). In the subsequent harvest, more of the analyzed element was found in the leaves of wheat grown after galega, on average by 21% (4.2 g kg^{-1}).

The lowest amount of Zn was found in wheat grain collected from fertilization variant F2 in the growth after galega and from fertilization variant F1 in the growth after rapeseed (Table 9). The best effects of foliar fertilization in the form of Zn concentration in the grain were found after the application of the mix of granules with the addition of Zn and Mn applied twice (F3). In the growth after galega, the increase was on average higher by 8% in comparison with variant F2. In the growth after rapeseed, an increase by 65% was noted in comparison with the grain collected from variant F1. In the growth after rapeseed, the concentration of the analyzed elements in the grain did not differ significantly between fertilization variants F1 and F2. In relation to the control plot, the application of the mix of granules with the addition of Zn and Mn applied twice (F3) had the most favorable effect. In fertilization variant F3, in wheat grown after rapeseed, there was 56% more Zn (12.8 mg kg^{-1}), whereas in wheat grown after galega there was 4% more (1.3 mg kg^{-1}).

Similarly, Mn concentration in the grain of wheat grown after galega was the highest in wheat fertilized with the mix of granules with the addition of Zn and Mn applied twice (F3) (Table 9). Grain collected from the above fertilizer combination had on average 27% more Mn than grain with its lowest content, collected from the plots fertilized with the mix of granules (F1). In growth after rapeseed, like in the case of Zn, Mn concentration did not differ significantly between fertilization variants F1 and F2. The highest amount of Mn was found in the grain of wheat fertilized with the mix of granules with the addition of Zn and Mn applied twice (F3), on average 85% more than in fertilization variants F1 and F2. In comparison with the control, the grain of wheat collected from fertilization variant F3 contained 22% more Mn (10.1 mg kg^{-1}) in the growth after galega and 82% more Mn (25.2 mg kg^{-1}) in the growth after rapeseed.

Foliar fertilization significantly increased K concentration in the grain of wheat grown after both pre-crop species (Table 9). No statistically significant differences were found in the contents of the analyzed elements between the particular fertilization variants (F1, F2, F3). As a result of foliar fertilization, regardless of the fertilization variant, a nearly ten-fold increase in K content was noted in the grain of wheat grown after galega and winter rapeseed in comparison with the control plot.

Grains of wheat grown after galega contained significantly more Zn and Mn compared to the grains of wheat grown after winter rapeseed, on average by 34% and 33%, respectively (9 mg kg^{-1} and 12 mg kg^{-1}). Pre-crop type did not diversify K concentration in the studied grain (Table 9).

4. Discussion

4.1. Yield and its Components

The average yield of the studied winter wheat was similar to the yields reported in the literature [30,43,44]. In the present study, winter wheat grain yield improved as a result of the applied pre-crop and the chosen variants of foliar fertilization. A better yield-forming effect was obtained in the crop after winter rapeseed, which was confirmed in earlier studies stating that yield in the subsequent winter wheat cultivations grown after winter rapeseed reached 0.76–0.98 t/ha^{-1} more than the yield of cultivations in monoculture [32]. Weather conditions in the growth years have a significant effect on winter wheat yield. In spite of constant enhancements in cultivation technology and cultivars, weather remains the major uncontrollable factor that significantly affects agricultural production. High temperatures may cause a significant decrease in grain yield, which results in a shortened grain-filling stage and increased leaf aging [45], potentially causing a serious decrease in grain number and mass [46]. High cereal yield usually depends on low precipitation during winter and in April, whereas higher precipitation is necessary at the straw-shooting and flowering stages. Bujak [47] implied a lack of correlation between yield and precipitation sum. Erekul and Kohn [48] demonstrated that a continued water deficit and above-average temperatures during grain filling lowered the TKW of winter wheat, which was not confirmed in the present study. TKW was significantly higher in the second study year, by 3.3 g, which may have resulted from a different weather pattern. August 2017 had approximately 74 mm more rainfall than average. Test weight is an important predictor of the flour extraction rate for wheat. Similarly to TKW, the higher ratio, of about 2.1 kg hL^{-1}, was noted in 2017.

Yield components do not affect the yield independently. Compensation is frequently observed between yield components due to their sequential development during ontogeny, during which they reach different values depending on the assumed agrotechnical factors and habitat conditions [49]. From the biological point of view, a lower grain yield of winter wheat grown after many-years' galega monoculture, in relation to the growth after winter rapeseed, may be the result of significantly lower TKW (by 26%) and, although not proven statistically, a lower number of ears per m^2. Griffiths et al. [50] demonstrated that the grain number per area unit is the yield component that correlates the most with grain yield. According to Weber and Biskupski [51], a higher winter wheat yield results from an increased number of ears per area unit, number of grains per ear and TKW. A decrease in the value of one yield structure characteristic may be compensated for by a more favorable effect of a different characteristic, which, within some limits, may neutralize yield decrease. In literature concerning both winter and spring wheat, a negative correlation between TKW and the number of grains per ear is underscored [52], which was confirmed in the present study. The number of grains per ear and ear length were significantly higher in wheat collected from plots after many-years' galega monoculture than in cereals grown after winter rapeseed. The above differences may result from the conditions of the habitat that, according to Rozbicki et al. [26], have a significantly greater effect on wheat grain yield than agrotechnical products.

Previous study results indicate a diverse effect of additional fertilization with Zn and Mn on wheat yield and its components. Zeidan et al. [53] noted a significant increase in the yield, TKW and grain number per ear after foliar application of Zn and Mn in wheat growth. Additionally, the results by Abbasi et al. [54] demonstrated that foliar application of zinc sulphate causes an increase in the TKW. The positive effect of Zn application on grain yield and its elements was confirmed by Sultana et al. [55] and Esfandiari et al. [56]. On the other hand, Li et al. [21] demonstrated that Zn application, regardless of the dose, has no effect on the yield. The studied wheat responded favorably to the applied foliar fertilization, and no statistically significant differences were found in yield size, the TKW and ear length between the particular fertilization variants (F1, F2, F3). All of the fertilization variants applied in the present study (F1, F2, F3) significantly increased grain yield, number of grains per ear, ear length and the TKW, which was confirmed in the studies by Gonzalez et al. [57] and Rerkasem et al. [58], who indicated that foliar application of nutrients increases yield and meets the need for nutrients in cultivations. It is more than likely that the positive effect of foliar Zn application results from the role it plays as an enzyme component or a coenzyme in a wide variety of enzymes [11,59]. It influences photosynthesis by affecting the activity of the carbonic anhydrase and chlorophyll content. Within a certain range of Zn concentration, the intensity of photosynthesis rises with the increase in Zn concentration [60]. Moreover, microelements such as Mn and Zn affect protein biosynthesis through the adaptation of peptidase activity and control of protein [61]. In plants, a decrease in the amount of K was observed as a result of a Zn deficit [20]. Potassium shortages may decrease photosynthetic CO_2 binding, as well as the transport and use of assimilates. According to Zafar et al. [62], joint application of K and Zn in foliar plant fertilization more effectively increased wheat yield and its components than the application of the above elements separately. In the present research, similar results were obtained, although no statistically significant difference in yield and its components was found between the particular fertilization variants (F1, F2, F3). However, a better yield-forming effect of a joint application of K and Zn may result from the key role of potassium in carbohydrate synthesis, nitrogen assimilation, photosynthesis, increased tolerance to drought and through foliar application as well as an increased availability and uptake of zinc [63–65].

4.2. Quality Properties of Grain and Dough

Falling number is one of the methods which determine the activity of the amylolytic enzymes in wheat grain; therefore, it should reach a minimum of 150 seconds for commercial purposes. Wheat grain for flour milling and then bread baking should be characterized by a falling number between 220 and 350 s, which indicates an average amylolytic activity [65]. This parameter is very sensitive to the variability of weather conditions and fertilization [28,66]. This was also reflected in our study, where the average falling number varied between 286 and 330 s depending on the foliar application and rainfall. In 2017, the rainfall in August reached 126 mm, which was twice as much compared to 2016, and resulted in a higher falling number (330 s). Humid weather during grain ripening contributes to increased amylolytic activity and grain growth [67]. The foliar application with Zn, Mn and K supplementation resulted in a significant (49 s) increase in the falling number compared to the control without foliar application. Despite reports stating that habitat conditions may affect falling numbers [68], we have not found such a relationship.

Grain protein concentration and composition are important quality measures. They define nutritional and end-use properties of dough mixing and rheological characteristics such as dough strength, development time, extensibility, breakdown and loaf volume; all of the above effect the efficiency of the bread making process and product quality [69]. Protein content is not only genetically inherited, but also significantly modified by agro practices and environmental factors [70]. This was also partially confirmed by our findings. A protein content of 11%–14% guarantees a high quality of wheat flour for bread [44,71]. In our study, the protein content in wheat grain varied between 12.7%–13.6% and depended on the pre-crop and weather conditions. Positive effects of *fabacea* plants cropped prior to wheat are commonly known in regard to the physico-chemical properties of soil and nitrogen remnants [30,43,72,73]. When wheat was grown subsequent to galega, our study revealed an increase of 0.9% in grain protein. In 2017, it became apparent that moderate rainfall and warm weather during harvest were conducive to higher protein content in grain, which is consistent with Harasim and Wesołowski [67]. Correspondingly, the galega habitat contributed to higher gluten content in wheat grain (4%) as compared to the rapeseed habitat. Our results are consistent with the findings of Babulicova and Gavurnikowa [30], which showed that wet gluten content in wheat grain increased when wheat was grown subsequent to pea as compared to cereal pre-crops. According to Başlar and Ertugay [74], both parameters are positively correlated. Our results indicated that the Pearson's correlation between protein and gluten content was significant as well (r = 0.82). As a result, experimental factors were either impacted or remained neutral in regard to the above. Previous findings revealed that foliar supplementation during grain formulation contributed to protein and gluten content in wheat grain [75,76]. In our study, however, foliar supplementation with Zn, Mn and K did not affect either the protein or the gluten content. Furthermore, our investigation showed that weather conditions might diminish this effect. In our study, gluten content was higher than Knapowski's et al. [44] but lower than the findings of Matus et al. [71]. Regardless of the experimental factors, the average gluten content reached 28.1% and 35.2% in 2016 and 2017, respectively. Wheat grain containing above 25% gluten guarantees high quality bread.

Gluten quality was evaluated on the basis of the gluten index. A higher gluten index indicates stronger gluten. An increase in the gluten index in the studied grain caused a decrease in protein concentration (r = −0.50). Wheat flour used for baking should be characterized by a gluten index between 60–70. The recommended gluten index value for wheat bread was obtained in the first study year (70.7), whereas in the second year it was exceeded significantly (99.2). The gluten index does not depend significantly on the pre-crop or the applied foliar fertilization. The value of the above characteristic was only diversified by the study year. Earlier study results demonstrated that the quantity and quality of cereal gluten was higher when, during grain ripening, the weather was warm and precipitation low [77], which is partly in agreement with the results of the present study. In the present study, higher gluten content was obtained in the period characterized by high precipitation. Temperatures were similar in both growing seasons.

One of the more important parameters that determine wheat grain quality is the Zeleny sedimentation index. It characterizes both the quantity and quality of gluten proteins, which determine bread structure [44]. The sedimentation index should reach over 20% in order to obtain optimal baking quality [68]. The sedimentation value is one of the best indicators of flour quality, due to favorable and positive correlations with the most important technological characteristics, such as protein content, which was confirmed by the present results. Significant correlation was found between the Zeleny sedimentation index and the total protein content ($r = 0.73$); with an increase in sedimentation value, the protein content in the grain also increased [44,78]. The effectiveness of foliar fertilizer application with added microelements for the improvement of the described parameter of flour quality was confirmed by Knapowski et al. [44]. In the present study, no significant differences were found between sedimentation values in the grain collected from the control plot and from the particular fertilization variants. Significant differences resulted only from the study year, which was also demonstrated by Stępień et al. [73].

4.3. Farinographic Properties of Grain and Flour

Habitat conditions, especially CO_2 concentration in the atmosphere and thermal shock during the grain-filling stage not only affect starch and protein deposition but also functional characteristics, including dough rheology and baking quality [79]. Tomić et al. [80] also reported high variability of the rheological parameters of wheat quality depending on the year and location. In the studied grain, higher values of rheological characteristics, with the exception of water absorption, were noted in the second, cooler, study year, which was characterized by lower temperatures in the growth season (from grain filling to harvest). Contrary to this, Tomić et al. [80] reported that higher rheological parameters were obtained in warmer season. In addition to the above, protein content, amount of gluten and sedimentation value also affect farinographic properties [79], which was confirmed in the present study. Dough obtained from the flour from wheat grown after galega was evaluated the most favorably because it was characterized by higher water absorption and longer dough development and stability. It is more than likely that this was caused by higher contents of protein, gluten and sedimentation value in the grain collected from that study combination. Water absorption values reached between 37.4% and 56.5%, depending on the pre-crop and harvest year. Generally high water absorption by flour is considered to be a symptom of good baking capability. The reason for this may be the fact that high protein content causes high baking capability and high water absorption [68]. Correlation coefficients obtained in the present study corresponded with the above statement. Highly significant correlations were found between the protein content in the grain and water absorption ($r = 0.88$), which was confirmed in another study [81]. Dough development time depends on the quantity and quality of gluten contained in the flour and its water binding capacity. Flour with poor gluten is characterized by short dough development time. Dough development time fell within the range of 1.83 to 2.09 and was dependent exclusively on the pre-crop. Stability is an indicator of flour tolerance to mixing. Stability of the analyzed dough varied between 1.76 and 2.62, depending on the pre-crop and harvest year. Higher protein concentration in the grain increased dough stability, which was confirmed by the noted highly significant correlation between protein content in the grain and stability ($r = 0.91$). Too-high dough softening during kneading is unfavorable because it may negatively affect bread quality. The degree of softening in the studied grain varied between 72.1 FU in the first study year and 85.0 FU in the second study year. According to classification, strong flour demonstrates water absorption of >59%, development of >3 min, consistency of >4 min and softening of <40 FU, while poor flour demonstrates water absorption of <51%, development of <2 min, consistency of <1 min and softening of >150 FU. The studied flour may be considered as medium, between poor and strong.

4.4. Zinc, Manganese and Potassium Content in Wheat Leaves and Grain Depending on the Habitat and Foliar Fertilization

Microelement content in plants depends first of all on the content of microelements in the soil and their availability for plants. The concentration of such microelements as Zn, Mn and Fe in plants strictly correlates with their content in the soil and its pH. As pH increases, the contents of Zn and Mn in the plant decrease [82]. In this study, soil pH varied between acidic (5.0) in galega growth and neutral (6.8) in winter wheat growth. Higher Zn and Mn contents were found in the leaves and grain of wheat grown after galega, which probably resulted from lower soil pH, and thus from higher bioavailability of those microelements by plants.

Zn concentration in wheat grain varies between wheat cultivars and depends on the habitat conditions, cultivation means, and developmental stage [23,83,84]. Critical Zn content in different plant parts oscillates between 12–20 mg kg^{-1} for young leaves and 20–35 mg kg^{-1} for grain [85,86]. Average Zn concentration in the studied cultivar, regardless of the pre-crop and fertilization, fell within the range of 13.1–16.3 mg kg^{-1} for leaves and 25.5–34.1 mg kg^{-1} for grain.

For the last few decades, micronutrient content (mainly Fe, Zn, Mg, and Cu) in edible products decreased in spite of their high concentration in the soil. Improving microelement transfer to the edible parts through remobilization from vegetative tissue may be a method of meeting the need for microelements. Zn remobilization from leaves to grain in wheat is significant, since over 50% of Zn in wheat grain comes from leaf remobilization [7,10]. Foliar Zn application appears to be, therefore, a promising method of Zn content increase in the grain, although its effectiveness may depend on several factors. Cakmak et al. [23] demonstrated that the highest Zn concentration in the grain was obtained by applying Zn on four dates, which may explain the fact that in the present study the best effect was obtained using foliar fertilization of the mix of granules with the addition of Zn and Mn applied twice (F3). Niyigaba et al. [86] also emphasized that Zn concentration in grain depends on its concentration in the fertilizer, and as Zn concentration increased, its content in the grain also increased. Similarly, Gomaa et al. [87] stated that that foliar application of nutrients caused an increase in Zn concentration in wheat grain, and the effect, according to Arif et al. [88], may be attributed mainly to the vital physiological roles in plant cells responsible for the root uptake of nutrients. Foliar application of a mix of granules with the addition of Zn and Mn applied twice (F3) also improved Mn concentration in the leaves and grain of the studied wheat. An increase in Mn concentration in wheat grain after the foliar application of Zn and Mn was also reported by Zeidan et al. [53]. Manganese takes part in several metabolic processes, mainly in photosynthesis, as the antioxidant cofactor enzyme. An excess of this microelement is toxic to plants, which manifests itself through decreasing biomass and photosynthesis, as well as biochemical disorders, such as oxidative stress. On average, the leaves of the studied wheat contained from 36.8 to 85.7 mg kg^{-1} Mn, and grain from 36.7 to 48.7 mg kg^{-1}. Wojtkowiak and Stępień [89] stated that average Mn content in wheat grain oscillated between 42.9 and 43.8 mg kg^{-1}, depending on the growth year.

Average potassium content oscillated between 19.6 and 23.8 g kg^{-1} in leaves and between 3.37 and 3.50 g kg^{-1} in grain, regardless of the habitat and fertilization. Grains of wheat grown after winter rapeseed and galega were characterized by similar K contents, in spite of the fact that in the soil after galega, significantly more available potassium was found. Presumably, wheat grown after galega was unable to uptake more of the above element due to low soil pH, and therefore the results of the additional foliar fertilization in both cultivations were similar. The potassium decrease is under stress factors such as drought, cold temperatures and high solar radiation.

5. Conclusions

Pre-crop type and cultivation year had the highest effect on yield, yield components, and qualitative and farinographic characteristics of winter wheat. Two yield components, TKW and grain number per m^2, directly affected the yield size of winter wheat grown after winter rapeseed. Foliar additional feeding favorably affected yield and its components, although the particular fertilization variants did not diversify its size. The highest concentrations of Zn, Mn and K were found in the leaves and grain of wheat fertilized with the mix of granules with the doses of Zn and Mn applied twice (F3). Grain quality, its physical characteristics and the rheological parameters of flour were strongly modified by habitat conditions, including weather conditions. TKW and test weight were significantly higher in the second study year. Grain collected from plots after galega had higher protein and gluten content, which confirms the favorable effect of legumes on winter wheat. Dough obtained from flour from wheat grown after galega was evaluated the most favorably. It was characterized by higher water absorption and longer development and consistency times of dough. With the exception of water absorption and gluten index, higher values of qualitative and farinographic characteristics of the analyzed grain occurred in the second, cooler (from grain filling to harvest), year of study.

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