agronomy

MDPI

Article

Pre-Anthesis Nutritional Status of Spelt Wheat as a Tool for Predicting the Attainable Grain Yield

Witold Grzebisz [1], Przemysław Barłóg [1,*], Jan Kryszak [2] and Remigiusz Łukowiak [1]

1 Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego 71F, 60-625 Poznan, Poland; witold.grzebisz@up.poznan.pl (W.G.); remigiusz.lukowiak@up.poznan.pl (R.Ł.)

2 Department of Grassland and Natural Landscape Sciences, Poznan University of Life Sciences, Dojazd 11, 60-632 Poznan, Poland; jan.kryszak@up.poznan.pl

* Correspondence: przemyslaw.barlog@up.poznan.pl; Tel.: +48-618-48-77-88

Received: 21 August 2019; Accepted: 15 September 2019; Published: 17 September 2019

check for updates

Abstract: The nutrient content in leaves of spelt wheat at late heading is crucial for the development of its yield components, and in consequence, grain yield. This hypothesis was verified based on data from long-term field experiments with four potassium (K) treatments based on the progressive K supply potential to plants from soil and fertilizer and two magnesium treatments (−Mg, +Mg). The number of ears (NE) and the number of grains per ear (NGE) responded significantly to the increased K and Mg supply. The grain yield was positively correlated with NGE. A shortage of N and Mg resulted in a lower NGE, whereas a shortage of N and Zn, concomitant with an excess of Ca, resulted in a significant decrease in NGE and thousand-grain weight. This effect can be diminished by the increased content of Mg. It has been revealed that the content of Zn in leaves of spelt wheat at heading is an important nutritional factor effectively controlling N, P and Fe contents in grain, and consequently, grain yield. This study showed that the content of nutrients in spelt leaves measured just before anthesis can be used for reliable prediction of the grain yield.

Keywords: application system; magnesium; potassium; *Triticum spelta*; yield components; yield-gap

1. Introduction

Spelt, the ancient bread wheat, is nowadays experiencing a renaissance in its production, with vastly increased areas being sown in Europe and North America [1]. The key reason for such renewed interest is its much healthier nutritional quality, including its content of proteins, lipids, fibers, vitamins, and nutrients as compared to common wheat [2,3]. Spelt wheat, in contrast to common wheat, is considered to be a crop that is highly tolerant to unfavorable growth conditions, including low soil fertility and low input of production measures. Therefore, it is cultivated mainly on organic farms, but grain yields are low and variable from year-to-year [4].

The increasing interest in food products based on spelt wheat flour is a major reason for the intensification of this wheat species production. There are considered to be two key ways of achieving success. The first refers to breeding progress. Presently, an increasing number of new high-yielding varieties are recorded. The second way comprises a set of agronomic measures, including soil quality and health, fore-crop, and doses of applied nutrients. As reported by Ugrenović et al. [5], yields of spelt wheat varieties, irrespective of weather conditions in consecutive years of study, were the highest on chernozem. The recent study by Wanic et al. [6] has fully corroborated this opinion. These authors showed that spelt is sensitive to growth conditions as created by preceding crops.

With respect to nutrient application, the most deeply studied is nitrogen (N). As clearly indicated by Sinclair and Jamieson [7], N management in cereals is a key factor responsible for both the number of grains set per ear and grain yield. Spelt wheat is considered as having low requirements for N fertilizer. This opinion has been recently corroborated by Andruszczak [8], who showed that a N dose of 80 kg ha^{-1} resulted in a grain yield decline, mostly due to lodging. The current efforts in bread wheat production are almost fully oriented to optimizing the N use efficiency of new cultivars in order to decrease its losses to the environment [9,10]. The low requirement for N by spelt, concomitant with its high-yielding potential, creates an alternative agronomic option for reducing the reliance of bread wheat production on doses of applied N fertilizers [11].

The impact of other basic nutrients on the productivity of this crop, including potassium (K) and magnesium (Mg) is, in fact, a black box. As recently published by Dhillon et al. [12], K use efficiency in cereals is low, amounting to 19%. The physiological functions of K as related to water management by crop plants are well recognized. Plants that are well supplied with K during the growing season are able to overcome, at least partly, the negative impacts of drought [13]. Magnesium, due to its predisposition to significant dilution in edible plant parts, requires careful attention from both consumers and breeders, but especially farmers [14,15]. The deficiency of Mg in the edible part of a crop plant can be solved in a complementary way. The first is a cultivation of crops naturally rich in Mg. Spelt wheat, due to naturally having much higher contents of numerous nutrients, including Mg, is a strategic option in future breeding programs [16–18]. The current, in fact, urgent solution for overcoming the Mg deficiency in wheat grain is soil or foliar application of Mg fertilizers [19].

In spite of extended reports on spelt wheat with respect to agronomy measures, there is a lack of studies concerning a diagnosis of its nutritional status during vegetative growth. The spelt wheat biomass and its partitioning between plant organs just before anthesis is an important trait, significantly affecting the development of yield components, and subsequently, grain yield [20]. The objective of this study was to evaluate the impact of nutrient concentration in leaves of spelt wheat just before anthesis, i.e., at heading, on the development of yield components, grain yield, and on the mineral nutrient content.

2. Materials and Methods

2.1. Site Description

Field trials with spelt wheat were carried out in 2013–2016 at the Brody Experimental Farm (Poznan University of Life Sciences, 52°44′ N; 16°28′ E). The study was based on an experimental long-term trial which was established in 1991 on Albic Luvisol and originated from loamy sand underlined by light loam [21]. The topsoil was characterized by an optimal soil reaction (Table 1). The amount of mineral N (N_{min}) measured in spring in a layer of 0–60 cm ranged from 44.4 kg ha^{-1} to 51.5 kg ha^{-1}. The topsoil samples taken from the K1 plot showed a low content of plant-available K; K2, medium; K3, medium; and K4, high. At a soil depth of 0.3–0.6 m, the differences in K content between treatments were less prominent than at a depth of 0–0.3 m, especially between K2 and K3 treatments. Moreover, the topsoil featured a high content of available P and Mg [22]. The long-standing K fertilization system did not have a significant influence on the content of the above elements in soil.

Meteorological data are presented in Figure 1. The total sum of precipitation during the spring growing season (March–July) was 284 mm in 2014, 272 mm in 2015, and 346 mm in 2016, whereas the long-term average for this period is 275 mm.

2.2. Experimental Design

The field trial was arranged as a two-factorial split-block design, replicated four times, and was comprised of two systems of nutrient application:

(1) four rates of potassium: K1 → 0 kg ha^{-1}; K2 → 18.75 kg ha^{-1}; K3 → 37.5 kg ha^{-1}; K4 → 75 kg ha^{-1},
(2) two rates of magnesium: 0 kg Mg ha^{-1}; 10.5 kg Mg ha^{-1} (7.5 + 3.0 kg Mg ha^{-1}).

The area of an individual plot was 22.4 m^2 (2.8 m × 8 m). The fore-crop for spelt wheat was oilseed rape. Ears of spelt (*Triticum spelta*, cultivar Ebners Rotkorn) were sown at a rate of 300 kg ha^{-1} at the end of September (seeding depth = 50 mm; row spacing = 150 mm). Rates and forms of nutrients applied two weeks before wheat sowing were as follows: (i) K as potassium salt (KCl; 49.8% pure K) in accordance with the experimental design, (ii) Mg as kieserite ($MgSO_4 \times H_2O$; 15.8% Mg) in accordance with the experimental design → 7.5 kg Mg ha^{-1}, (iii) P at the rate of 19.8 kg ha^{-1} as single superphosphate. Magnesium applied (3.0 kg Mg ha^{-1}) to wheat foliage at beginning of stem elongation (according to the BBCH scale 31; BBCH *in German*: Biologische Bundesanstalt, Bundessortenamt and CHemische Industrie) was in the form $MgSO_4 \times 7H_2O$ (9.6% Mg). Nitrogen as ammonium nitrate (34% N) was applied in one dose of 60 kg ha^{-1} at the beginning of spring vegetation.

Table 1. Soil chemical properties as a result of stationary long-term field experiments, varied K fertilization (mean for three years).

Soil Depth, m	K Treatment	pH[1]	P[2]	K[2]	Mg[2]	Ca[2]	NH_4-N[3]	NO_3-N[3]	N_{min}[3]
			mg kg^{-1}				kg ha^{-1}		
0–0.3	K_1	6.5	153.4	91.5	72.0	1213	3.7	29.4	33.1
	K_2	6.5	154.0	110.3	70.5	1169	3.9	26.7	30.6
	K_3	6.5	154.3	129.5	72.0	1219	3.5	29.4	32.6
	K_4	6.6	152.4	163.7	75.0	1166	4.5	31.6	36.1
0.3–0.6	K_1	6.1	61.0	68.5	90.5	1390	3.8	12.2	16.0
	K_2	6.2	63.5	80.0	84.0	1401	3.7	10.1	13.8
	K_3	5.9	65.0	86.5	105.5	1293	3.8	12.3	16.1
	K_4	6.1	69.5	104.5	98.0	1328	3.7	11.7	15.4

[1] 1.0 mol KCl; [2] Mehlich 3 method; [3] 0.01 mol $CaCl_2$.

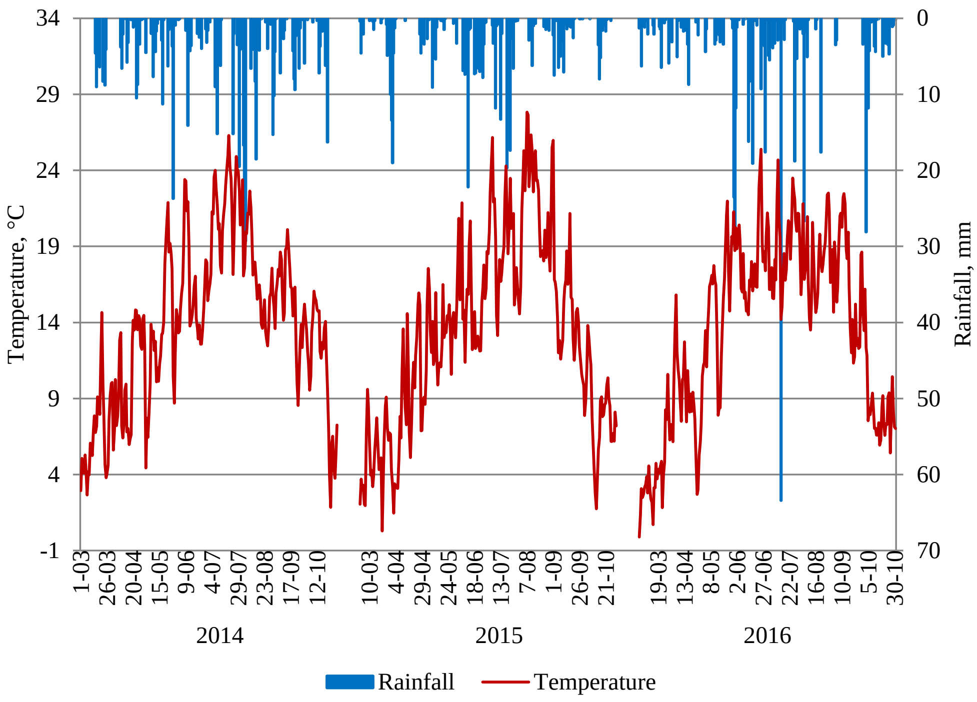

Figure 1. Mean daily air temperature and precipitation during the 2014–2016 growing seasons, measured at the Synoptic Station at Brody.

2.3. Experimental Measurements and Chemical Analysis

Soil samples were collected twice a year, in summer (after harvest of forecrop) and at the beginning of spring vegetation. Soil samples were taken using a manual Eijkelkamp auger (Eijkelkamp Soil and Water, Giesbeek, Nederland) from topsoil (0–0.3 m) and subsoil (0.3–0.6 m) of each field representing different K fertilization. After air-drying, soil properties were determined according to the standard method: pH in 1.0 mol KCl (soil/solution ratio 1:2.5; w/v) and plant-available P, K, Ca and Mg by the Mehlich 3 method [23]. The NH_4-N and NO_3-N were determined in field-fresh soil samples. Twenty grams of soil samples were shaken for 1 h with 100 mL of a 0.01 M $CaCl_2$ solution (soil/solution ratio 5:1; w/v). Concentrations of NH_4-N and NO_3-N were determined with the colorimetric method using flow injection analyses (FIAstar 5000, FOSS Analytical AB, Sweden). Concentrations of K, Mg, and Ca in the collected extracts were analyzed by atomic absorption spectrophotometry (SpectrAA 55B, Varian, Australia). The concentration of P was determined by the colorimetric method using a spectrophotometer Specord 40 (Analitik Jena, Germany).

Plant material used for the determination of dry matter (DM) and nutrient content was collected from an area of 0.2 m^2 at spelt wheat heading (according to the BBCH scale 56–58). Grain was collected during harvest (BBCH 89). The total grain yield (GY) harvested from an area of 12 m^2 was adjusted to a 14% moisture content. The nitrogen content was determined using a standard macro-Kjeldahl procedure (Kjeltec Auto 1031 Analyzer, FOSS Analytical AB, Sweden). For other nutrients, the harvested plant sample was dried at 55 °C and then mineralized at 600 °C. The obtained ash was then dissolved in 33% HNO_3. The phosphorus concentration was measured by the vanadium–molybdenum method using a Specord 40 (Analytik Jena, Jena, Germany) at a wavelength of 436 nm. The potassium concentration was measured by flame photometry and other nutrients by atomic absorption spectrometry.

2.4. Yield-Gap Calculation

The yield-gap (loss) was calculated based on the index, termed as the Partial Factor Productivity of N fertilizer (PFP_N). It expressed the gross productivity of the applied N fertilizer [24]. The $cPFP_N$ average for the third quarter of the ascending PFP_N data set was used as the critical value for the maximum yield calculation (GY_{MAX}). The yield-gap calculation procedure comprised the following set of equations:

$$PFP_N = GY / N, \tag{1}$$

$$GY_{MAX} = cPFP_N \times N, \tag{2}$$

$$GY\text{-}L = GY - GY_{MAX}, \tag{3}$$

where, PFP_N—Partial Factor Productivity of N fertilizer, kg kg^{-1}; GY—grain yield, kg ha^{-1}; N—nitrogen fertilizer rate, kg N ha^{-1}; GY_{MAX}—maximum of GY, kg ha^{-1}; $cPFP_N$—the average of the third quarter; GY-L—yield-gap, kg ha^{-1}.

2.5. Statistical Analysis

The effects of individual research factors (year, potassium, magnesium) and their interactions on the grain yield and mineral nutrient contents were assessed by means of a three-way ANOVA. Means were separated by honest significant difference (HSD) using Tukey's method, when the F-test indicated significant factorial effects at the level of $p < 0.05$. The effects of factors on the seed yield and mineral nutrient contents were compared by means of a one-way ANOVA (year, potassium, magnesium), or two-way ANOVA (interaction between factors). The relationships between the traits were analyzed using Pearson correlation and linear regression. The stepwise regression was applied to define the optimal set of variables for plant characteristics. The best regression model was selected based on the highest *F*-value for the entire model. STATISTICA 12 software was used for all statistical analyses [25].

3. Results

3.1. Grain Yield and Yield Components

The grain yield of spelt wheat was significantly dependent on the interaction of experimental treatments and weather (Figure 2, Table 2). The effect of weather was the decisive grain yield factor, being slightly modified by experimental factors. The effect of K treatments (soil K fertility level + current K application) was only significant with respect to the control plot (+9.5%). The same level of impact was found for Mg, resulting in a grain yield increase of 8.2%. The lowest grain yield, as recorded in 2014, was due to a shortage of precipitation during most of the spring vegetation (Figure 1). In this year, the effect of increasing K treatment was negligible, but Mg treatment resulted in a yield increase in contrastive K plots (K1 and K4). In 2015, a year with drought in the summer months, the grain yield was double as compared to 2014. The impact of K rates was highly variable, but it responded significantly to Mg application. The observed trend corroborates data for other crops which are very sensitive to Mg fertilization in years with drought [26]. In 2016, a favorable year with respect to the amount and distribution of precipitation, the yields were the highest, showing a significant response to the interaction of K and Mg when applied in high rates. This is in agreement with the opinion of Grzebisz [19], who stated that Mg application was an effective nutritional measure for exploiting a crop yielding potential under optimal growth conditions.

Table 2. Grain yields of spelt wheat and yield components.

Factor	Level of Factor	GY[1] t ha^{-1}	NE No m^{-1}	NGE No ear^{-1}	SD No m^{-2}	TGW g	PFP$_N$ kg kg^{-1}	GY-L t ha^{-1}
Year (Y)	2014	2.43^a	610.0^b	18.2^a	11212	28.9^a	32.4^a	−2.351^a
	2015	3.79^b	568.4^b	22.1^b	12597	54.8^b	63.1^b	−0.996^b
	2016	4.48^c	504.2^a	22.9^b	11639	51.5^b	74.6^c	−0.308^c
F-value		230.8***	15.4***	41.7***	2.83	977.6***	410.8***	230.8***
K rate kg ha^{-1}	0.0	3.33^a	555.6^{ab}	19.4^a	10745^a	44.8	52.9^a	1.457^b
	18.8	3.66^b	536.5^a	20.9^{ab}	11164^a	45.1	58.5^b	1.208^a
	37.5	3.65^b	599.6^b	22.6^c	13573^b	45.7	57.8^b	1.138^a
	75.0	3.63^b	551.8^{ab}	21.4^{bc}	11782^{ab}	44.7	57.7^b	1.159^a
F-value		4.08**	3.00**	8.50***	6.55***	0.81^{ns}	4.39**	4.1**
Mg rate kg ha^{-1}	0.0	3.42^a	548.1	20.4^a	11151^a	44.7	54.5^a	1.360^b
	10.5	3.71^b	573.7	21.8^b	12481^b	45.5	59.0^b	1.078^a
F-value		12.9***	2.65	9.42***	7.46**	2.73	13.1***	12.9***
F-values for interaction								
Y × K		6.09***	1.04^{ns}	0.76^{ns}	1.05^{ns}	0.69^{ns}	6.61***	6.09***
Y × Mg		0.22^{ns}	0.28^{ns}	0.01^{ns}	0.05^{ns}	1.42^{ns}	0.47^{ns}	0.22^{ns}
K × Mg		2.24^{ns}	0.26^{ns}	0.47^{ns}	0.35^{ns}	1.16^{ns}	2.26^{ns}	2.24^{ns}
Y × K × Mg		3.65**	1.10^{ns}	0.93^{ns}	1.12^{ns}	2.73*	3.49**	3.65**

[1] Abbreviations: GY—grain yield; NE—number of ears; NGE—number of grains per ear; SD—seed density; TGW—thousand-grain weight; PFP$_N$—Partial Factor Productivity of N fertilizer; GY-L—yield-gap. ***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively; ns—not significant; the same letter indicates a lack of significant differences within the treatment.

Yield-gap (GY-L) is a measure of N inefficiency. The value of the Partial Factor of Nitrogen Productivity (PFP$_N$), as calculated for the third quarter of PFP$_N$, amounted to 79.7 kg grain per 1.0 kg of applied N. The lowest PFP$_N$ of 32.4 kg kg^{-1} N was recorded in 2014. It was twice as low as compared to 2015. In 2016, PFP$_N$ reached the highest value of 75 kg kg^{-1} N, i.e., at the level of 94% of the calculated maximum. The range obtained clearly corroborated the opinion of the decisive impact of environmental conditions on the N productivity of spelt wheat [27]. The maximum attainable grain yield (GY$_{MAX}$) under conditions of the study based on PFP$_N$ of 79.7 kg kg^{-1} amounted to 4784 kg ha^{-1} (4.78 t ha^{-1}). This yield level of spelt wheat is achievable, provided favorable growth conditions, which are defined by a high soil fertility level, favorable weather conditions during the grain-filling period and a high quality of the fore-crop [5,6]. The yield loss (GY-L) in 2014 was almost equal to the harvested yield. In 2015, it was much lower, constituting 21% and in 2016, only 6% of the attainable yield (Table 2). The existing yield-gap was partly covered by the interactional effect of experimental factors, but its power depended on weather in consecutive years. The net grain yield gain (GY-G) was achieved in 2016 on treatments with the highest rates of K and Mg (Figure 2).

The course of the weather was the key factor affecting the variability of yield components of spelt wheat. The number of ears and the number of grains per ear showed a strong compensation mechanism, which resulted in a constant seed density in all the years of study. It is necessary to stress that the thousand-grain weight (TGW) was positively correlated with the number of grains per ear, but at the same time, negatively correlated with the number of ears (Table 3). The positive relationship between the number of grains per ear and TGW clearly indicates that competition for assimilates between the number and the enlarging grains during the grain-filling period did not occur [28]. The low TGW, as recorded in 2014, can be explained by a disturbance in the supply of assimilates from leaves to the developing grains during the grain-filling period. The impact of fertilization treatments on yield components was the most consistent only for the seed density. The effect of increasing K rates on seed density (SD) was best described by the quadrate regression model:

$$SD = -1.236\ K^2 + 112.6\ K + 10{,}402 \text{ for } R^2 = 0.69,\ n = 24 \text{ and } p = 0.554. \quad (4)$$

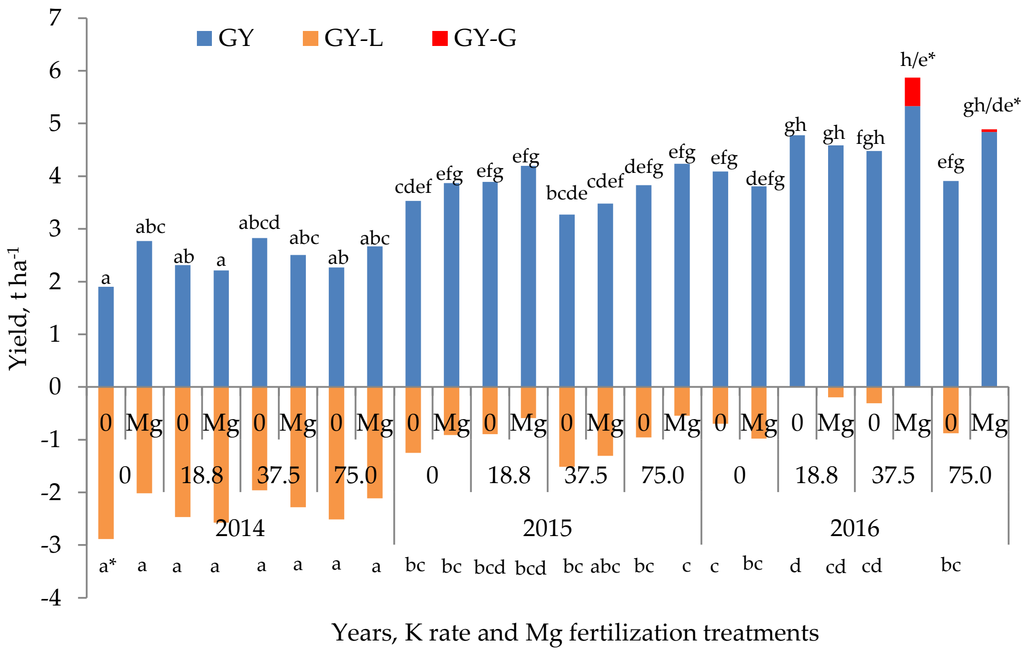

Figure 2. Effect of fertilization treatments on the grain yield (GY), yield-gap (GY-L) and net grain yield gain (GY-G) of spelt wheat depending on the year. Potassium rates: 0 kg K ha^{-1}, 18.8 kg K ha^{-1}, 37.5 kg K ha^{-1}, 75.0 kg K ha^{-1}; 0 kg Mg ha^{-1}—control, without Mg fertilization; Mg—magnesium fertilization (10.5 kg Mg ha^{-1}). The same letter indicates a lack of significant differences within the treatment; *—test for the GY-L.

A maximum seed density of 12,966 grains m^{-2} was recorded for a K rate of 45.6 kg ha^{-1}. The recorded seed density was consistent with the increase in both the number of ears and number of grains per ear. The significant effect of applied Mg was recorded only for the number of grains per ear. The key reason for poor grain yield in 2014 was an extremely low thousand-grain weight, explicitly indicating a disturbance in the supply of assimilates to grains during the grain-filling period. It is well documented that the N concentration in leaves of cereals during the grain-filling period is decisive for the rate of photosynthesis and longevity of leaves, treated as a source of assimilates for the growing grain [29]. The stepwise regression analysis clearly showed that the grain yield (GY) of spelt was driven by the number of ears (NE) and the number of grains per ear (NGE):

$$GY = 0.9 - 0.0054\ NE + 0.269\ NGE \text{ for } R^2 = 0.79,\ n = 24 \text{ and } p < 0.001. \quad (5)$$

The unit productivity of fertilizer N (PFP_N) significantly depended on the degree of development of these two yield components, and TGW values:

$$PFP_N = 0.47 - 0.078\ NE + 3.334\ NGE + 0.662\ TGW \text{ for } R^2 = 0.87, n = 24 \text{ and } p < 0.001. \quad (6)$$

This equation indirectly stresses the importance of K and Mg application as agronomic measures for exploiting the yielding potential of spelt wheat. Their effect resulted from the significant and positive impact of applied nutrients on both NGE and PFP_N (Table 2).

3.2. Grain Yield Prediction Based on Nutrient Concentration in Leaves at Heading

The heading phase of wheat growth is considered to have the highest photosynthetic capacity, being responsible for the grain set per ear [30,31]. Therefore, the nutritional status of wheat plants at this particular phase seems to be a crucial factor for the expression of yield components. The study clearly demonstrated that the content of nutrients in wheat leaves at the end of heading (BBCH 56–58) was significantly driven by the course of weather. The content of N, P, K, and Cu decreased in the order 2015 > 2016 > 2014 (Table 3). All these nutrients were significantly correlated with each other (Table 4). Nitrogen was the only nutrient to show a significant response to K treatments. As a rule, a much higher content of N was recorded in plants fertilized with K. It is well-documented that K is the key cation required during the grain-filling period for assimilate transportation from leaves to the growing grains [32]. The shortage of both N and K in wheat leaves, as recorded in 2014, explains the lower TGW, which subsequently led to a low grain yield.

Table 3. Nutrient content in leaves of spelt wheat at heading (BBCH 56–58).

Factor	Level of Factor	N	P	K	Mg	Ca	Mn	Zn	Cu
				g kg^{-1}				mg kg^{-1}	
Year (Y)	2014	12.4^a	2.4^a	23.0^a	1.7^b	0.3^b	45.7^a	14.1^a	2.1^a
	2015	23.5^c	3.9^c	31.0^c	1.0^a	0.2^a	47.1^{ab}	13.9^a	5.7^c
	2016	19.4^b	3.3^b	26.2^b	2.5^c	0.2^a	51.9^b	24.1^b	3.9^b
	F-value	166.5***	129.9***	36.8***	274.5***	123.7***	3.36*	84.0***	160.8***
K rate kg ha^{-1}	0.0	16.9^a	3.2	25.5	1.7	0.3	47.5	17.5	3.9
	18.8	19.0^b	3.2	26.5	1.6	0.3	51.1	16.7	4.0
	37.5	19.0^b	3.2	28.1	1.7	0.3	48.6	18.2	3.9
	75.0	18.7^b	3.1	26.8	1.7	0.3	45.7	16.8	3.8
	F-value	3.87*	1.23^{ns}	1.90^{ns}	1.33^{ns}	0.33^{ns}	1.20^{ns}	1.77^{ns}	0.34^{ns}
Mg rate kg ha^{-1}	0.0	18.5	3.2	26.9	1.7	0.3	49.4	16.8	4.0
	10.5	18.3	3.1	26.5	1.7	0.3	47.1	17.9	3.8
	F-value	0.12^{ns}	1.36^{ns}	0.33^{ns}	2.22^{ns}	0.12^{ns}	1.27^{ns}	0.02^{ns}	2.54^{ns}
					F-values for interaction				
Y × K		0.12^{ns}	1.87^{ns}	0.43^{ns}	0.75^{ns}	1.60^{ns}	1.11^{ns}	0.87^{ns}	0.36^{ns}
Y × Mg		1.09^{ns}	0.32^{ns}	1.60^{ns}	0.89^{ns}	0.26^{ns}	1.61^{ns}	0.07^{ns}	0.74^{ns}
K × Mg		0.12^{ns}	1.44^{ns}	0.59^{ns}	1.23^{ns}	3.32*	1.20^{ns}	3.53*	1.39^{ns}
Y × K × Mg		0.46^{ns}	0.7^{ns}	0.45^{ns}	2.90*	1.31^{ns}	1.87^{ns}	1.75^{ns}	0.36^{ns}

BBCH—Biologische Bundesanstalt, Bundessortenamt and CHemische Industrie. ***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively; ns—not significant; the same letter indicates a lack of significant differences within the treatment.

The most grain-yield-limiting factor was Ca, the concentration of which increased due to water stress (Table 4). At the same time, its concentration was positively correlated with NE, but negatively with NGE and TGW. The analysis of Table 4 clearly illustrates that the contents of N, P, K, Cu and Zn were crucial for both NGE and TGW development. It can be concluded that any decrease in the contents of these four nutrients plus Zn resulted in significantly lower NGE and TGW. This opinion was fully corroborated by the applied stepwise regression, which showed that both NGE and GY were significantly controlled by almost the same set of nutrients:

$$TGW = 38.6 - 67.1\ Ca + 4.81\ Cu + 0.29\ Zn \text{ for } R^2 = 0.98, n = 24 \text{ and } p < 0.001 \quad (7)$$

$$NGE = 9.08 + 0.48\ N + 1.89\ Mg \text{ for } R^2 = 0.70, n = 24 \text{ and } p < 0.001 \quad (8)$$

$$GY = -0.47 + 0.12\ N + 0.10\ Zn \text{ for } R^2 = 0.84, n = 24 \text{ and } p < 0.001 \quad (9)$$

The key reason for the high Ca concentration in leaves of spelt wheat at heading was drought. The spelt grain yield was also the lowest in this particular year. Therefore, the highest Ca concentration, as recorded in 2014, concomitant with a simultaneously lower concentration of K and N indicates an imbalance status of both nutrients in spelt wheat. The amount of soil-available Ca was in the suitable class. The amount of available K was in the low class for the K1 treatment and in the suitable class for other treatments. Therefore, these two nutrients were well-balanced in the soil. It is well-documented in the scientific literature that a shortage of K negatively affects the rate of plant growth [33].

The shortage of the same set of nutrients, in combination with an excess of Ca, was the main reason for the PFP_N development:

$$PFP_N = 29.94 + 1.66\ N - 105.1\ Ca + 1.34\ Zn \text{ for } R^2 = 0.93, n = 24 \text{ and } p < 0.001. \quad (10)$$

The effect of Ca on PFP_N, and consequently, on the GY, was indirect—through other nutrients—because it exerted a strong negative impact on the content of basic nutrients, such as N, P, K and also on Cu, which were positively correlated with grain yield (Table 4). The applied stepwise regression analysis showed that the yield-gap decreased in accordance with the increase in N and Zn contents in leaves of spelt wheat during late heading (Figure 3).

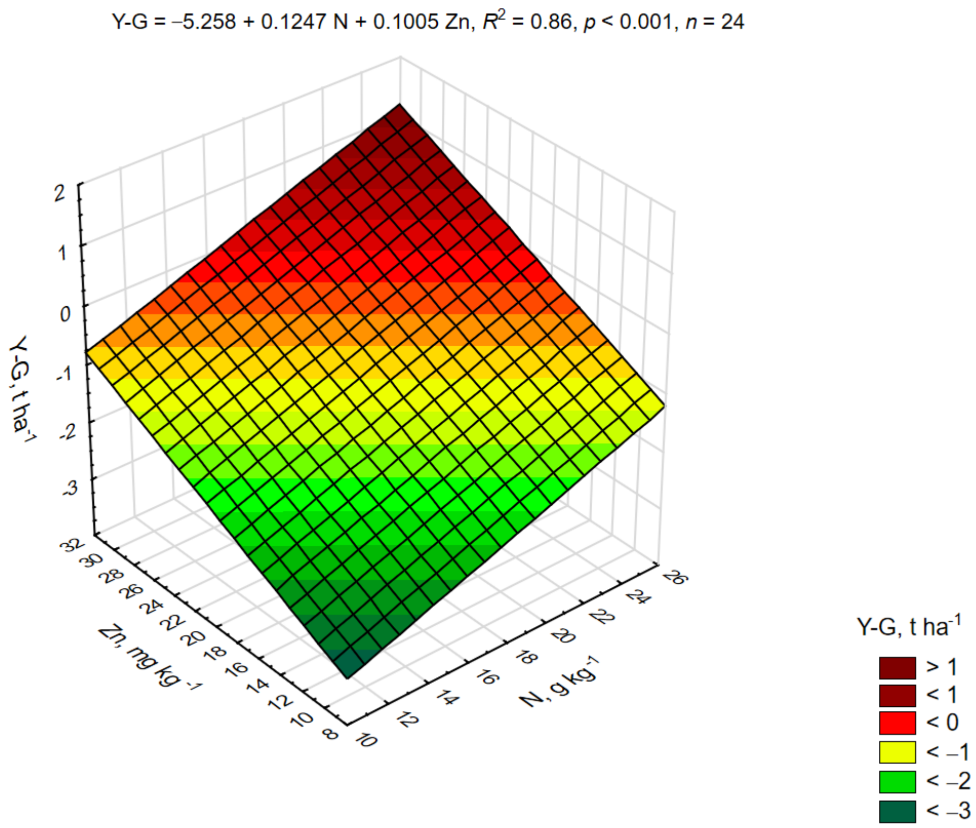

Figure 3. The grain yield-gap (GY-L) as a function of contents of N and Zn in spelt leaves at heading.

The nutrient status of spelt wheat, as measured just before anthesis, can be taken as a reliable diagnostic tool for the GY prediction. The pre-anthesis phase, i.e., heading, is treated for other cereals as the diagnostic phase for the evaluation of nutritional status or for the yield prediction. The classical example of information in the first area is the book by Bergmann [34]. It contains data of optimal ranges of nutrient concentration for wheat and other cereals. The calcium content in leaves was found to be a stressful growth factor, negatively influencing two yield components, i.e., NGE and TGW. The excesses of Ca significantly disturbing the content of N, P, K, and Cu subsequently led to a decrease in NGE and TGW. The shortage of N is considered as the key factor responsible for the variability in NGE, subsequently resulting in the GY variability [7]. The simultaneous reduction in these two yield components resulted in the development of a yield-gap (GY-L). The results obtained corroborate the opinion by Ugrenović et al. [5] that spelt wheat is not tolerant to both harsh environmental conditions and low soil fertility.

Table 4. Correlation matrix between contents of nutrients in leaves of spelt wheat, yield components and yield traits, n = 24.

Traits	P	K	Mg	Ca	Mn	Cu	Zn	NE[1]	NGE	TGW	GY	PFP_N
N	0.93***	0.89***	−0.33	−0.76***	0.13	0.95***	−0.11	−0.38	0.73***	0.94***	0.71***	0.77***
P		0.89***	−0.34	−0.71***	0.15	0.97***	−0.07	−0.37	0.61**	0.91***	0.60**	0.67***
K			−0.50*	−0.47*	0.18	0.91***	−0.10	−0.12	0.59**	0.77***	0.44*	0.51*
Mg				−0.23	0.30	−0.43*	0.77***	−0.39	0.18	−0.07	0.34	0.29
Ca					−0.13	−0.65**	−0.50**	0.69***	−0.74***	−0.90***	−0.88***	−0.91***
Mn						0.13	0.33	−0.35	0.22	0.18	0.28	0.28
Cu							−0.01	−0.31	0.56**	0.90***	0.57**	0.64**
Zn								−0.39	0.47*	0.34	0.67***	0.64**
NE [1]									−0.27	−0.51*	−0.54**	−0.57**
NGE										0.78***	0.84***	0.84***
TGW											0.84***	0.89***
GY												0.99***

[1] Abbreviations: NE—number of ears; NGE—number of grains per ear; TGW—thousand-grain weight; GY—grain yield; PFP_N—Partial Factor Productivity of N fertilizer. ***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively.

3.3. Nutrient Content in Grain and its Relation to Grain Yield

The nutrient content in the grain of spelt wheat was significantly governed by weather during consecutive growing seasons (Table 5). The content of N, in spite of a significant dependence on the K and Mg interaction, showed the lowest year-to-year variability, as corroborated by a coefficient of variation (CV) of 4.2%. The high N stability can be explained by both the conservative trait of the N content in spelt grain and a relatively low dosage of applied N fertilizer. The first hypothesis is frequently discussed in numerous papers, which stress a high N content in the grain of spelt wheat, irrespective of the impact of external conditions, such as soil fertility level or environmental stresses [35,36]. The second opinion is corroborated by the fact that high N fertilizer doses result in the excessive growth of stems, leading to their lodging and in turn resulting in yield decline [8].

It is necessary to stress that N content was negatively correlated with the contents of all studied nutrients, except P and iron (Fe). The highest negative impact of N was recorded for Mg, followed by Cu and Mn (Table 6). The highest decrease in the contents of these nutrients, except P and Fe, was recorded in 2015, a year that experienced water shortages during the grain-filling period. Even more interesting is the fact that N content in leaves of spelt at heading negatively affected the content of the same set of nutrients, except N and P (Table 7).

Table 5. Nutrient concentration in spelt wheat grain at maturity.

Factor	Level of Factor	N	P	K	Mg	Ca	Fe	Mn	Zn	Cu
				g kg^{-1}					mg kg^{-1}	
Year (Y)	2014	23.7^{ab}	2.3^{b}	4.6^{b}	0.97^{b}	0.31^{c}	40.8^{c}	18.6^{b}	21.2^{b}	3.2^{ab}
	2015	24.7^{b}	3.2^{c}	3.7^{a}	0.77^{a}	0.15^{a}	35.1^{b}	13.7^{a}	18.7^{a}	2.3^{a}
	2016	22.7^{a}	1.6^{a}	4.5^{ab}	1.11^{c}	0.29^{b}	29.3^{a}	21.7^{c}	23.1^{c}	3.3^{b}
	F-value	9.92***	189.4***	34.6***	121.1***	281.4***	35.3***	58.0***	16.9***	18.6***
K rate kg ha^{-1}	0.0	23.8	2.4	4.2	0.94	0.23	34.2	18.0	21.7	2.8
	18.8	24.1	2.4	4.1	0.95	0.27	35.3	17.0	20.9	2.8
	37.5	23.1	2.4	4.2	0.96	0.24	33.8	17.8	20.2	3.2
	75.0	23.7	2.3	4.4	0.97	0.25	36.8	19.3	21.3	2.9
	F-value	1.32^{ns}	0.11^{ns}	1.10^{ns}	0.29^{ns}	4.12**	1.49^{ns}	2.31^{ns}	0.98^{ns}	1.39^{ns}
Mg rate kg ha^{-1}	0.0	23.9	2.4	4.2	0.95	0.25	35.4	17.8	20.9	2.9
	10.5	23.5	2.4	4.3	0.96	0.24	34.7	18.3	21.1	2.9
	F-value	1.20^{ns}	0.03^{ns}	2.57^{ns}	0.61^{ns}	2.68^{ns}	0.36^{ns}	0.60^{ns}	0.04^{ns}	0.08^{ns}
					F-values for interaction					
	Y × K	1.29^{ns}	0.96^{ns}	0.46^{ns}	0.33	4.90***	0.39^{ns}	0.66^{ns}	2.33*	1.07^{ns}
	Y × Mg	0.16^{ns}	0.48^{ns}	0.07^{ns}	0.04	0.63^{ns}	0.35^{ns}	0.62^{ns}	0.34^{ns}	0.44^{ns}
	K × Mg	0.80^{ns}	2.27^{ns}	4.29**	2.22	15.2***	1.73^{ns}	0.49^{ns}	0.80^{ns}	0.15^{ns}
	Y × K × Mg	3.45**	0.85^{ns}	0.19^{ns}	0.69	11.1***	0.24^{ns}	1.16^{ns}	0.64^{ns}	0.33^{ns}

***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively; ns—not significant; the same letter indicates a lack of significant differences within the treatment.

Table 6. Correlation matrix between contents of nutrients in grain of spelt wheat, $n = 24$.

Traits	P	K	Mg	Ca	Fe	Mn	Cu	Zn	NE	NGE	TGW	GY	PFP_N
N	0.58**	−0.37	−0.54**	−0.40	0.28	−0.39	−0.51*	−0.50*	−0.03	−0.23	0.03	−0.37	−0.30
P		−0.72***	−0.93***	−0.73***	0.48*	−0.71***	−0.79***	−0.89***	0.39	−0.07	0.21	−0.19	−0.14
K			0.79***	0.82***	0.08	0.69***	0.79***	0.82***	−0.03	−0.28	−0.59**	−0.22	−0.29
Mg				0.77***	−0.43*	0.83***	0.78***	0.96***	−0.42*	0.13	−0.17	0.26	0.20
Ca					0.09	0.71***	0.75***	0.77***	−0.12	−0.38	−0.65**	−0.25	−0.32
Fe						−0.28	−0.08	−0.32	0.72***	−0.62**	−0.71***	−0.79***	−0.81***
Mn							0.68***	0.85***	−0.39	0.03	−0.24	0.15	0.12
Cu								0.81***	−0.51*	−0.03	−0.15	−0.11	−0.17
Zn									−0.04	−0.05	−0.46*	0.17	0.11
NE										−0.27	−0.51**	−0.54**	−0.57**
NGE											0.78***	0.84***	0.84**
TGW												0.84***	0.89***
GY													0.98***

[1] Abbreviations: NE—number of ears; NGE—number of grains per ear; TGW—thousand-grain weight; GY—grain yield; PFP_N—Partial Factor Productivity of N fertilizer. ***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively.

Table 7. Relationships between the contents of nutrients in leaves of spelt wheat at heading and in the grain at maturity, $n = 24$.

Variables	N_g [2]	P_g	K_g	Mg_g	Ca_g	Fe_g	Mn_g	Zn_g	Cu_g
N_h [1]	0.17	0.42*	−0.71***	−0.37	−0.74***	−0.49*	−0.42*	−0.29	−0.56**
P_h	0.26	0.45*	−0.75***	−0.41*	−0.75***	−0.49*	−0.46*	−0.34	−0.59**
K_h	0.24	0.56**	−0.80***	−0.57**	−0.81***	−0.27	−0.60**	−0.54**	−0.64**
Mg_h	−0.67***	−0.94***	0.65**	0.91***	0.68***	−0.55**	0.86***	0.72***	0.75***
Ca_h	0.13	0.11	0.25	−0.21	0.30	0.82***	−0.11	−0.20	0.21
Mn_h	−0.03	−0.32	0.01	0.27	0.09	−0.40	0.16	0.16	0.10
Zn_h	−0.64**	−0.68***	0.22	0.67***	0.23	−0.74***	0.61**	0.43*	0.42*
Cu_h	0.30	0.54**	−0.83***	−0.53**	−0.83***	−0.42*	−0.58**	−0.45*	−0.72***

***, **, * significant at $p < 0.001$; < 0.01; < 0.05, respectively; [1] $_h$—heading; [2] $_g$—grain.

The highest year-to-year variability in the mineral nutrient content in spelt grain was recorded for P and Ca. The highest P content was recorded in the dry 2015, and the lowest in the wet 2016, being concomitant with the highest yield (Table 5). The P content was positively correlated with N and Fe, but negatively with all other nutrients (Table 6). Its content in spelt leaves at heading showed a negative impact on the content of all nutrients in grain, except N and P (Table 7). The highest negative relationships were observed for K and Ca. These negative relationships, combined with tendency of the P content to dilution as recorded in 2016, but at the same time a lack of the significant impact on PFP_N and grain yield, indicate an excess of P in spelt leaves at heading.

Calcium concentration showed a reverse pattern of year-to-year variability as compared to P. The highest Ca concentration was recorded in 2014, a year with the lowest grain yield. The increased Ca content negatively affected TGW. The Ca content was negatively correlated with P and N, but positively with other nutrients, except Fe (Table 6). However, the key information is that the Fe concentration in the grain (Fe_g) was the only nutrient that significantly correlated with Ca concentration in spelt leaves at heading (Ca_h):

$$Fe_g = 21.7 + 50.3\ Ca_h \text{ for } R^2 = 0.67, n = 24 \text{ and } p < 0.001. \quad (11)$$

The Fe content in spelt grain, through the negative impact on TGW, was revealed as the single GY indicator:

$$GY = 9.397 - 0.169\ Fe_g \text{ for } R^2 = 0.61, n = 24 \text{ and } p < 0.001. \quad (12)$$

From the results from the stepwise regression analysis, TGW showed a positive response to the increase in the P content, but at the same time, showed a negative response to the increase in the Fe content:

$$TGW = 112.8 + 12.1\ P_g - 2.79\ Fe_g \text{ for } R^2 = 0.88, n = 24 \text{ and } p < 0.001. \quad (13)$$

These three relationships clearly indicate that the Ca content in leaves (Ca_h), determined just before wheat anthesis, is the primary reason for the negative impact of Fe_g on the quantitative status of yield components such as NGE, TGW, and finally, the grain yield.

Contents of K and Mg in spelt wheat grain showed a three-fold and two-fold lower year-to-year variability, respectively, when compared to Ca (Table 5). The K content was in the range frequently published [2]. The Mg content was the highest in 2016, a year with the highest grain yield, but the lowest in the dry 2015. In the dry 2015, the Mg concentration was lower by 30%, whereas the grain yield was 15% lower, as compared to 2016. These two figures clearly indicate that the Mg content in grain can be effectively managed, provided high soil fertility, combined with the favorable amount and distribution of precipitation. These results clearly indicate the decisive impact of water availability in a given growing season on Mg uptake by cereals [19]. The Mg content of 1.11 g kg^{-1} DM was much higher than recorded for common wheat, but at the same time lower as compared to frequently published data for spelt wheat [17].

In spite of expectation, Ca and Mg contents in spelt grain (Ca_g and Mg_g), were significantly correlated with each other (Table 6). However, both nutrients impacted NGE differently, as shown by the following equation:

$$NGE = 13.1 + 0.02\ Mg_g - 0.04\ Ca_g \text{ for } R^2 = 0.56, n = 24 \text{ and } p < 0.001. \quad (14)$$

The regression model obtained clearly shows that the reduced NGE, as recorded in 2014, was due to the indirect impact of Ca in the leaves of spelt wheat measured just before anthesis. The most important message, referring to Mg, is that its increased content in spelt grain resulted in the lower contents of N, Fe, and especially of P (Table 6). These trends were due to the high Mg content in leaves of spelt just before anthesis. The ameliorative impact of the Mg content in spelt leaves at heading on the content of Fe in grain indicates its anti-stress functions during the grain-filling period of spelt wheat (Table 7).

The heading phase is a stage for correcting the nutritional disorder of cereals. In the studied case, the practical solution is to apply magnesium sulfate (Epsom salt) to ameliorate the water shortage, at least partly [19]. This practice is usually recommended for common wheat. As reported by Samar Raza et al. [37], K applied under drought conditions to wheat foliage at different stages of growth significantly narrowed the K:Ca uptake ratio. The most sensitive stage to K foliar application was the grain-filling period. Our study corroborates the positive yield-forming role of foliar Mg application, resulting in both higher yield and Mg content in the grain [19]. The content of micronutrients in spelt grain was, in general, lower as compared to frequently published data [17,38]. This study showed that the increasing content of K and Mg in the grain resulted in a simultaneous increase in the contents of Mn, Zn, and Cu. The impact of micronutrient contents in spelt leaves at heading on their contents in the grain was significant only for Zn. Its content negatively affected N, P, and Fe contents in the grain, and consequently through PFP_N increase, finally led to the increase in the GY of spelt wheat.

4. Conclusions

This study clearly showed that the effective exploitation of the yielding potential of spelt wheat depends on the interactional effect of weather and a high level of soil fertility. The primary reason for nutrient disorders in leaves of spelt wheat at heading was drought, which resulted in the excessive concentration of Ca with respect to N, K, and Cu. The Ca concentration was revealed as the primary nutritional factor affecting nutrient accumulation in the grain during the grain-filling period, consequently leading to the excess content of Fe, which in turn decreased the number of grains per ear, thousand-grain weight, resulting in the development of the grain yield-gap. The increase in the number of grains per ear, through the positive impact of K and Mg fertilization leading to the progressive Partial Factor Productivity of N fertilizer (PFP_N) increase, resulted in a decrease in the grain yield-gap. The post-harvest analysis of nutrient contents in the grain of spelt wheat showed that the negative impact of Ca on the number of grains per ear and thousand-grain weight could be controlled by the increased content of Mg. The Zn content in leaves of spelt wheat at heading was revealed as an important nutritional factor effectively controlling N, P, and Fe contents in the grain, PFP_N, and consequently, the grain yield. It can be concluded that the effective exploitation of spelt wheat yielding potential requires the use of K and Mg fertilizers for increasing N productivity and also for controlling nutritional stresses, such as the excess Ca content in spelt leaves during the pre-anthesis growth period.

Author Contributions: Conceptualization, W.G.; methodology, W.G. and P.B.; validation, P.B. and J.K.; formal analysis, W.G.; investigation, J.K. and R.Ł.; resources, J.K. and R.Ł.; data curation, W.G. and R.Ł.; writing—original draft preparation, W.G. and P.B.; writing—review and editing, W.G. and P.B.; visualization, W.G. and P.B.; supervision, W.G.; project administration, W.G.

Funding: This publication is being co-financed by the framework of Ministry of Science and Higher Education program as "Regional Initiative Excellence" in years 2019–2022, project no. 005/RID/2018/19.

Acknowledgments: The authors would like to thank K+S KALI GmbH for support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wilson, J.D.; Bechtel, D.B.; Wilson, G.W.T.; Seib, P.A. Bread quality of spelt wheat and its starch. *Cereal Chem.* **2008**, *85*, 629–638. [CrossRef]
2. Arzani, A.; Ashraf, M. Cultivated ancient wheats (*Triticum spp.*): A potential source of health-beneficial food products. *Compr. Rev. Food Sci. Food Saf.* **2017**, *16*, 477–488. [CrossRef]
3. Kohajdová, Z.; Karovičová, J. Nutritional value and baking applications of spelt wheat. *Acta Sci. Pol. Technol. Aliment.* **2008**, *7*, 5–14.
4. Konvalina, P.; Stehno, Z.; Capouchova, I.; Moudry, J. Wheat growing and quality in organic farming. In *Research in Organic Farming*; Nokkoul, R., Ed.; IntechOpen: London, UK, 2011; pp. 105–122. [CrossRef]

5. Ugrenović, V.; Bodroža-Solarov, M.; Pezo, L.; Disalov, J.; Popocić, V.; Marić, B.; Filipović, V. Analysis of spelt variability (*Triticum spelta* L.) grown in different conditions of Serbia by organic conditions. *Genetika* **2018**, *50*, 635–646. [CrossRef]
6. Wanic, M.; Denert, M.; Treder, K. Effect of forecrops on the yield and quality of common wheat and spelt wheat grain. *J. Elementol.* **2019**, *24*, 369–383. [CrossRef]
7. Sinclair, T.R.; Jamieson, P.D. Grain number, wheat yield, and bottling beer: An analysis. *Field Crop. Res.* **2006**, *98*, 60–67. [CrossRef]
8. Andruszczak, S. Spelt wheat grain yield and nutritional value response to sowing rate and nitrogen fertilization. *J. Anim. Plant Sci.* **2018**, *28*, 1476–1484.
9. Hawkesford, M.J. Reducing the reliance on nitrogen fertilizer for wheat production. *J. Cereal Sci.* **2014**, *59*, 276–283. [CrossRef]
10. Zörb, C.; Senbayram, M.; Peiter, E. Potassium in agriculture - status and perspectives. *J. Plant Physiol.* **2014**, *171*, 656–669. [CrossRef] [PubMed]
11. Koutroubas, S.D.; Fitiadis, S.; Damalas, C. Biomass and nitrogen accumulation and translocation in spelt (*Triticum spelta*) grown in a Mediterranean area. *Field Crop. Res.* **2012**, *127*, 1–8. [CrossRef]
12. Dhillon, J.S.; Eickhoff, E.M.; Mullen, R.W.; Raun, W.R. World potassium use efficiency in cereal crops. *Agron. J.* **2019**, *111*, 889–896. [CrossRef]
13. Grzebisz, W.; Gransee, A.; Szczepaniak, W.; Diatta, J. The effects of potassium fertilization on water-use efficiency in crop plants. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 355–374. [CrossRef]
14. Davis, D. Declining fruit and vegetable nutrient composition: What is the evidence? *Hortic. Sci.* **2009**, *44*, 16–19. [CrossRef]
15. Guo, W.; Nazim, H.; Liang, Z.; Yang, D. Magnesium deficiency in plants: An urgent problem. *Crop J.* **2016**, *4*, 83–91. [CrossRef]
16. Packa, D.; Załuski, D.; Graban, Ł.; Lajszner, W. An evaluation of spelt crosses for breeding new varieties of spring spelt. *Agronomy* **2019**, *9*, 167. [CrossRef]
17. Suchowilska, E.; Wiwart, M.; Kandler, W.; Krska, R. A comparison of macro- and microelement concentrations in the whole grain of four *Triticum* species. *Plant Soil Environ.* **2012**, *58*, 141–147. [CrossRef]
18. Xie, Q.; Mayes, S.; Sparkes, D.L. Spelt as a genetic resource for yield component improvement in bread wheat. *Crop Sci.* **2015**, *55*, 2753–2765. [CrossRef]
19. Grzebisz, W. Crop response to magnesium fertilization as affected by nitrogen supply. *Plant Soil* **2013**, *368*, 23–39. [CrossRef]
20. Xie, Q.; Mayes, S.; Sparkes, D.L. Preanthesis biomass accumulation of plant and plant organs defines yield components in wheat. *Eur. J. Agron.* **2016**, *81*, 15–26. [CrossRef]
21. WRB. World reference base for soil resources 2014. In *Word Soil Resources Reports*, *106*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2015. Available online: http://www.fao.org/3/a-i3794e.pdf (accessed on 8 July 2019).
22. Kęsik, K. Zastosowanie metody Mehlich 3 w systemie doradztwa nawozowego. In *Innowacje w Nawożeniu*; Studia i Raporty IUNG-PIB; Jadczyszyn, T., Rutkowska, A., Eds.; Institute of Soil Science and Plant Cultivation: Pulawy, Poland, 2016; Volume 48, pp. 95–104. (In Polish)
23. Mehlich, A. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Commun. Soil Sci. Plan.* **1984**, *15*, 1409–1416. [CrossRef]
24. Grzebisz, W.; Łukowiak, R.; Sassenrath, G. Virtual nitrogen as a tool for assessment of nitrogen management at the field scale: A crop rotation approach. *Field Crop. Res.* **2018**, *218*, 182–194. [CrossRef]
25. StatSoft Inc. *Electronic Statistics Textbook*; StatSoft: Tulsa, OK, USA, 2013. Available online: http://www.statsoft.com/textbook/ (accessed on 11 February 2019).
26. Gerendas, J.; Führs, H. The significance of magnesium for crop quality. *Plant Soil* **2013**, *368*, 101–128. [CrossRef]
27. Koutroubas, S.D.; Fitiadis, S.; Damalas, C.; Papageorgiu, M. Grain-filling patterns and nitrogen utilization efficiency of spelt (*Triticum spelta*) under Mediterraneoum conditions. *J. Agric. Sci. Camb.* **2014**, *152*, 716–730. [CrossRef]
28. Acreche, M.M.; Slafer, G.A. Grain weight response to increases in number of grains in wheat in a Mediterranean area. *Field Crop. Res.* **2006**, *98*, 52–59. [CrossRef]

29. Gaju, O.; Allard, V.; Martre, P.; le Gouis, J.; Moreaus, D.; Bogard, M.; Hubbart, S.; Foulkes, M.J. Nitrogen partitioning and remobilization in relation to leaf senescence, grain yield and grain nitrogen concentration in wheat cultivars. *Field Crop. Res.* **2014**, *155*, 213–223. [CrossRef]
30. Evans, L.; Wardlow, I. Aspects of the comparative physiology of grain yield in cereals. *Adv. Agron.* **1975**, *28*, 301–359.
31. Faroog, M.; Wahid, A.; Siddique, K.H.M. Physiology of grain development in cereals. In *Handbook of Plant and Crop Physiology*, 3rd ed.; Pessarakli, M., Ed.; Taylor and Francis Group: Boca Raton, FL, USA, 2014; pp. 301–311.
32. Haeder, H.E.; Beringer, H. Long distance transport of potassium in cereals during grain filling in detached ears. *Physiol. Plant.* **1984**, *62*, 433–438. [CrossRef]
33. Cakmak, I. The role of potassium in alleviating detrimental effects of abiotic stresses in plants. *J. Plant Nutr. Soil Sci.* **2005**, *168*, 521–530. [CrossRef]
34. Bergmann, W. *Nutritional Disorders of Plants*; Gustav Fisher: Jena, Germany, 1992.
35. Escarnot, E.; Jacquemin, J.M.; Agneessens, R.; Paquot, M. Comparative study on the content and profiles of macronutrients in spelt and wheat, a review. *Biotechnol. Agron. Soc. Environ.* **2012**, *16*, 243–256.
36. Gomez-Becerra, H.F.; Erdem, H.; Yazici, A.; Tutus, Y.; Torun, B.; Ozturk, L.; Calmak, I. Grain concentrations of protein and mineral nutrients in large collection of spelt wheat groan under different environments. *J. Cereal Sci.* **2010**, *52*, 342–349. [CrossRef]
37. Samar Raza, M.A.; Farrukh Saleem, M.; Mustafa Shah, G.; Jamil, M.; Haidar Khan, I. Potassium applied under drought improves physiological and nutrient performances of wheat (*Triticum Aestivum* L.). *J. Soil Sci. Plant Nutr.* **2013**, *1391*, 175–185. [CrossRef]
38. Wojtkowiak, K.; Stępień, A. Nutritive value of spelt (*Triticum aestivum* spp. *spelta* L.) as influenced by the foliar application of copper, zinc, and manganese. *Zemdirb. Agric.* **2015**, *102*, 389–396. [CrossRef]