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ORIGINAL PAPER

Potassium and magnesium deficiency in soil: the effect of mineral supplementation on organically grown winter spelt*

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Abstract

The aim of this study was to evaluate the effectiveness of supplementary K and Mg mineral fertilization on winter spelt yield and grain quality. Two 4-year field experiments investigating the effects of mineral fertilization on winter spelt (*Triticum spelta* L.) were conducted on Zgniłobłoty and Budziszewo organic farms with a long history of organic management. The first experiment was established on medium-heavy soil, and the second experiment – on heavy soil. Patentkali fertilizer was applied at 66.4 kg K ha^{-1} and 16.1 kg Mg ha^{-1}, and sulfate of potash (Kalisop) was applied at 66.4 kg K ha^{-1}. Since both fertilizers contain sulfur (S), supplemental S was supplied at 45 kg ha^{-1} (Patentkali) and 23.9 kg ha^{-1} (Kalisop). Winter spelt cv. Schwabenkorn was grown on medium-heavy soil. Soil pH was slightly acidic; content of available K was very low, and the content of available P, Mg, and S was moderate. Wheat spelt cv. Oberkulmer Rothkorn was grown on heavy soil. Soil pH was neutral; P content was low; K content was very low; Mg content was very high, and S content was moderate. The preceding crops were red clover in Zgniłobłoty (medium-heavy soil) and ley in Budziszewo (heavy soil). In the first experiment, the average spelt yield was 5.94 ha^{-1} of hulled grain and 4.27 t ha^{-1} of dehulled grain. Dehulled grain yields increased by 16.6% in response to mineral fertilization with K and Mg, and by 10.2% in response to K fertilization. Fertilized spelt produced larger grains with higher protein content. In the second experiment, the average spelt yield was also relatively high, at 5.76 and 4.20 t ha^{-1} of hulled and dehulled grain, respectively. Spelt yields tended to be higher when mineral fertilizers were applied to heavy soil. Protein content and concentrations of P, K, Mg and Ca in grain did not differ significantly between treatments fertilized with K+Mg and the unfertilized control treatment.

Keywords: winter spelt, organic farming, potassium, magnesium, soil deficiency, mineral supplementation

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INTRODUCTION

The productivity of Polish soils is generally low for several reasons, including low humus content (Kuś 2015, Zimnoch et al. 2024). Humus has a significant influence on the physical and chemical stability of soil, and chemical stability plays a particularly important role in organic farming. The availability of nutrients present in the parent rock is enhanced in soils with high levels of biological activity.

Acidity also poses a considerable problem in most Polish soils. In organic farming, pH control should be the first step in the soil improvement strategy. In 2015, 36.1% of agricultural land in Poland was highly acidic (pH (KCl) < 4.5) and 29.2% was acidic (pH (KCl) – 4.5 to 5.5) – Siebielec et al. (2017). Based on the analyses, it was shown that in recent years, 28.9% of the tested soil samples were characterized by a very acidic reaction, 28.3% of samples were acidic, 22.4% of soil samples were slightly acidic, 12.5% of soil samples were neutral, and 7.9% of soil samples were alkaline (https://wapno-info.pl/wp-content/uploads/2022/11/133556-spw-raport-zakwaszenie-gleb-wydanie-ii-luty-2022.pdf)

The low productivity of Polish soils can also be attributed to their low macronutrient content. According to a study conducted by the Institute of Soil Science and Plant Cultivation in 2015, 32% of soils had a very low or a low content of available forms of potassium (K); 48% of soils had a very low or a low content of available forms of phosphorus (P), and 27% of soils had a very low or a low content of available forms of magnesium (Mg) – Siebielec et al. (2017). Mineral and organic fertilizers play a key role in improving soil nutrient status and fertility (Radulov et al. 2011, Ali et al. 2019). It should be noted that unbalanced fertilization can lead to soil degradation and a decrease in productivity due to disruptions in ion homeostasis in the soil environment. Fertilization induces the biggest changes in soil pH and in the content of exchangeable P, K and Mg. The chemical properties of soil are significantly affected by the crop production system and fertilization (Stępień, Kobiałka 2019, Balik et al. 2023, Tavares et al. 2024).

Potassium is a macronutrient that is absorbed in greatest quantities by plants. Potassium participates in many metabolic processes in plants, including in the control of resistance to biotic and abiotic stresses. Potassium is a cofactor of more than 60 enzymes, and it is also involved in nutrient translocation from leaves to other plant parts, which decreases leaf sweetness, reduces the prevalence of insect-pests and, consequently, minimizes the demand for expensive pesticides. Potassium markedly influences crop yields and their quality (Sardans, Peñuelas 2021, Mostofa et al. 2022, Rawat et al. 2022). Phosphorus is one of the most important macronutrients necessary for crop development; without this element, there would be no yield. It is worth noting that phosphorus is a key factor in strengthening plant resistance to adverse environmental conditions (Khan et al. 2023).

Magnesium is yet another macronutrient that exerts a considerable impact on physiological processes in plants, abiotic stress tolerance, yield formation, and yield quality (Senbayram et al. 2015). Higher doses of Mg fertilizers are required in intensive crop production systems (Guo et al. 2016). For example, modern high-yielding cultivars of cereals and vegetables are more deficient in minerals (including Mg) than low-yielding cultivars (Guo et al. 2016). In intensive crop production systems, Mg released by soil minerals is generally insufficient to sustain high crop yields and quality (Wivstad et al. 2023).

In organic farming, the demand for mineral fertilizers depends on the nutrient balance (defined as the difference between nutrient inputs entering a farming system with manure and nutrient inputs leaving the system with the produced crops), and the abundance of nutrients in different soil types (Wivstad et al. 2023). Due to their origin, light sandy soils are generally deficient in nutrients. Research has shown that medium-heavy and heavy soils are generally more abundant in nutrients than light soils. This observation contributed to the mistaken belief that medium-heavy and heavy soils do not require mineral fertilization.

Mineral fertilizers had not been applied for more than 20 years in the studied farms. Nutrient deficiency commonly affects organic farms where soil is fertilized exclusively with farmyard manure (FYM). According to Jaskulska et al. (2015), even regular manure supply without balanced mineral fertilization will decrease winter wheat grain yields and quality in the long run. Arif (2017) argued that K removed with products should be replenished with balanced K fertilization to sustain soil fertility and optimum crop productivity in the long term. The demand for mineral fertilizers is usually higher in "old" organic farms that have been operated for 10-20 years. In many cases, K and/or Mg deficiencies are asymptomatic, and they can also occur also in "new" organic farms that have been managed for 1-5 years. In the latter case, these deficiencies are usually caused by the low initial content of nutrients in soil.

Studies comparing nutrient levels in European organic and conventional farms have demonstrated that K is removed from soil in the greatest quantities, especially in commercial vegetable farms (Wivstad et al. 2023). A negative potassium balance exceeding 30 kg ha^{-1} per year can cause yield losses (Nikitina et al. 2024). These studies were undertaken to assess the impact of organic and conventional farming systems on the environment and soil properties. Disruptions in the K and Mg balance were reported mostly in conventional farms, but K and Mg deficiencies were also frequently observed in organic farms (Reimer et al. 2020, Nikitina et al. 2024). Reimer et al. (2020) report that under organic farm conditions there is a negative potassium balance of -12 kg Mg ha^{-1} year^{-1} on average and a positive magnesium balance of +16 kg Mg ha^{-1} year^{-1}. Farms without livestock were most deficient in K, and K levels were much higher in farms with high stocking rates, in particular those that purchased straw (Wivstad et al. 2023). Not all organic livestock farms have to apply mineral fertilizers to supplement K and Mg. The demand for mineral fertilizers increases under extraordinary circumstances, such as overwintering losses of red clover (when the crop was plowed in) or typical symptoms of K deficiency on cereal leaves.

The aim of this study was to evaluate the effectiveness of additional mineral fertilization with potassium and magnesium on the yield and certain quality characteristics of grain of winter spelt wheat. The working hypothesis was that supplementary mineral fertilization can improve winter spelt yield and quality.

MATERIALS AND METHODS

Field experiment

Two field experiments investigating the effect of mineral fertilization on winter spelt were conducted in organic farms in Brodnica district, Kuyavia-Pomerania Province, Poland. Both experiments had a randomized block design (RBD) with four replications. The plot size (10 x 50 m) was optimized to the operating parameters of farm machines. Only the central part of the plot was harvested (400 m^2).

The first experiment (2007-2010) was established on medium-heavy soil in a certified organic farm in Zgniłobłoty, Poland (53.2833°N, 19.2333°E). The soil was classified as a Luvisol consisting of clay loam (WRB 2022). Before the study, the farm had been organically managed for 22 years, and it was characterized by an appropriate crop rotation scheme and a stocking rate of 0.7 LUs ha^{-1} (beef cattle). Farmyard manure was produced and applied regularly at 15 t ha^{-1} every other year.

The second experiment (2011-2014) was established on heavy soil in a certified organic farm in Budziszewo, Poland (53.3667°N, 19.1333°E). The soil was classified as a Gleyic Stagnic Eutric Cambisol (Loamic, Drainic) according to IUSS Working Group WRB (2022). Before the study, the farm had been organically managed for 26 years, and it was characterized by an appropriate crop rotation scheme and a stocking rate of 1.8 LUs ha^{-1} (dairy cattle). Farmyard manure was produced and applied regularly at 25 t ha^{-1} every other year.

It is worth noting that land-use intensity was relatively high on both farms. Perennial legumes (primary source of N) were incorporated into crop rotation, crops were extensively rotated, FYM was applied regularly (nutrient recycling), soil was tilled, and weeds were controlled (harrowing) with the use of traditional methods to guarantee high yields.

The experimental factor was mineral fertilization with K+Mg (Patentkali) and sulfate of potash (Kalisop), compared with the unfertilized control treatment.

Meteorological data

Groundwater and precipitation were the main sources of water in both farms. Weather conditions differed considerably in the growing seasons of winter spelt between 2006/2007 and 2013/2014, and greater variations were noted in daily precipitation than temperature (Figure 1). Considerable fluctuations in daily temperature relative to the long-term average were observed only in winter (December-March in Poland). Beginning in April, daily temperatures significantly exceeded the long-term average, and the highest temperatures were noted during spelt maturation in July and August. Even greater variations were observed in precipitation levels, which exceeded the long-term average in May, June, and July. Weather conditions were generally conducive to winter spelt cultivation in all seasons, and temperature and precipitation were adequate in the critical stages of plant growth and development.

Two winter spelt cultivars, Schwabenkorn and Oberkulmer Rothkorn, were grown in the experiments. Schwabenkorn is a winter-hardy cultivar that is well suited for organic cultivation on weak to medium soils (Bundessortenamt 2017). This long-stem cultivar scored 8 points (on a scale of 1-9 points) for pathogen resistance, and it is characterized by moderate susceptibility to *Blumeria graminis* f. sp. *tritici* and *Puccinia recondite* f. sp. *tritici,* as well as low to moderate susceptibility to *Zymoseptoria tritic*i. This cultivar is also characterized by high yields (3.5-4.2 t ha^{-1}) and satisfactory thousand grain weight (TGW) (42-45 g). Oberkulmer Rothkorn is also a winter-hardy cultivar, but its yields are lower than in other spelt cultivars, including Schwabenkorn (Bundessortenamt 2017). This longest-stem spelt cultivar is moderately susceptible to *Blumeria graminis* f. sp. *tritici*, *Puccinia recondite* f. sp. *tritici,* and *Puccinia striiformis* f. sp. *tritici,* and its susceptibility to *Zymoseptoria tritici* is low to moderate. In comparison with Schwabenkorn, Oberkulmer Rothkorn is characterized by somewhat lower yields (3.6-4.3 t ha^{-1}), but higher TGW (49-55 g).

Soil properties and fertilizer rates

Soil properties in the experimental sites were determined in the field and in a laboratory. In the field, pits were dug to a depth of 1.50 m to evaluate soil morphology and classify soil based on its properties. In Zgniłobłoty farm, soil had clay loam texture and was classified as medium-heavy. In Budziszewo farm, soil had clay texture and was classified as heavy (Table 1) (Soil Survey Staff 2011).

The chemical properties of soil were determined in representative samples collected with the Egner's cane at a depth of 0-20 cm. The samples were dried, ground, and sieved, and they were analyzed to determine:

- pH in a suspension of 1 mol KCl dm^{-3} solution, by potentiometric titration (PN-ISO 10390: 1997);

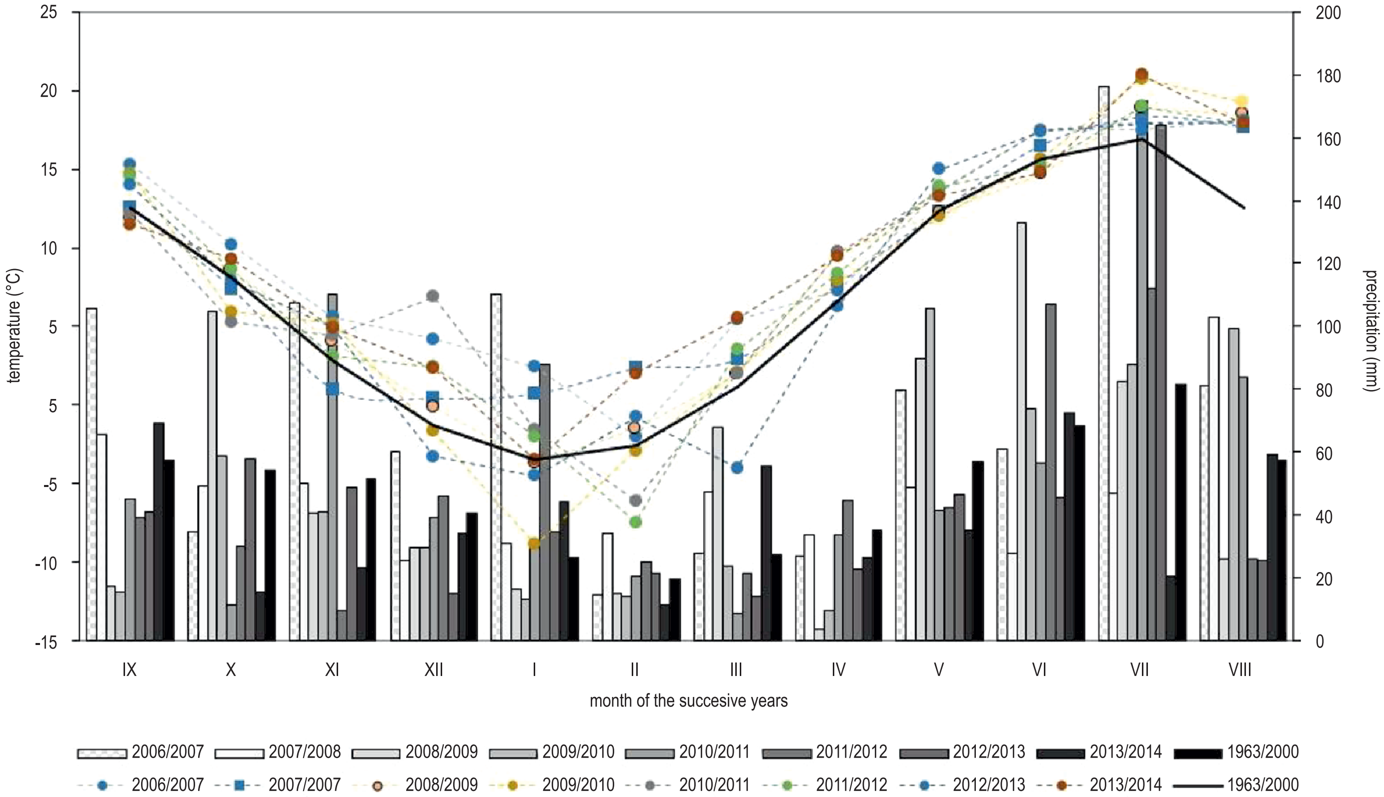

Fig. 1. Mean monthly temperatures and monthly precipitation totals in successive years of the study

Table 1

Physical properties of soils in organic farms in Zgniłobłoty and Budziszewo

Specification	Farm location	
	Zgniłobłoty	Budziszewo
Texture class	clay loam	clay
Soil horizon: 0-30 cm		
Sand (%)	39	22
Silt (%)	32	36
Clay (%)	29	42
Soil horizon: 30-150 cm		
Sand (%)	38	12
Silt (%)	31	32
Clay (%)	31	56

- content of available P and K, with the Egner-Riehm's method (PN-R-04022:1996/Az1: 2002, PN-R-04023: 1996);
- content of available Mg, with the Schachtschabel's method (PN-R-04020:1994/Az1: 2004);
- content of available S, with the nephelometric method (Ostrowska, Gawliński 1991);
- organic carbon content, with the Tiurin's method (Tyszkiewicz et al. 2019).

In the first experiment, conducted between 2007 and 2010, winter spelt cv. Schwabenkorn was grown after red clover. The following crop rotation scheme was applied: red clover – red clover – spelt – cabbage – spring wheat. Based on the recommendations of the Institute of Soil Science and Plant Cultivation (Ochal 2015), soil pH was classified as slightly acidic; the content of P, Mg and S was moderate, and K content was very low (Table 2).

In the second experiment, conducted between 2011 and 2014, winter spelt cv. Oberkulmer Rothkorn was grown after ley. The following crop rotation scheme was applied: ley – ley – ley – spelt – mixed cereals (wheat, barley, oats). Organic carbon content was 14.56 g kg^{-1} of soil, which is relatively low for heavy soils, but much higher than the Polish average. Soil pH was neutral, P content was low, K content was very low, Mg content was very high, and S content was moderate – Table 2 (Ochal 2015).

Under the conditions of the study, no mineral nitrogen fertilizers were used – winter spelt was organically grown. The N source for crops was: N nitrogen precipitation from the atmosphere (approx. 17 kg ha^{-1} year^{-1}), humus decomposition and nitrogen left behind by previous crops (ley and red clover). In both experiments, mineral fertilizers were applied before spelt sowing. The K+Mg fertilizer (Patentkali) and Kalisop were applied to the soil surface and incorporated into the soil with a tillage set (toothed harrow +

Table 2

Selected chemical properties of medium-heavy and heavy soils (0-30 cm) in organic farms in Zgniłobłoty and Budziszewo

Chemical properties	Unit	Location, soil type	
		Zgniłobłoty, medium-heavy soil	Budziszewo, heavy soil
Organic C	g kg^{-1} of soil	9.74	14.56
pH (1 mol KCl dm^{-3})		5.65	6.72
pH (H_2O)		6.29	7.39
Available ingredients			
P	mg kg^{-1} of soil	65.10	41.20
K	mg kg^{-1} of soil	55.70	82.80
Mg	mg kg^{-1} of soil	41.80	107,00
S-SO_4	mg kg^{-1} of soil	24.30	29.10
B	mg kg^{-1} of soil	0.45	0.70
Cu	mg kg^{-1} of soil	2.10	2.60
Mn	mg kg^{-1} of soil	124.80	115.30
Zn	mg kg^{-1} of soil	6.50	6.90
Fe	mg kg^{-1} of soil	1110.00	1210.00

cage roller). The applied fertilizers and their doses are presented in Table 3. Patentkali was applied at 66.4 kg K and 16.1 kg Mg ha^{-1}, and Kalisop was applied at 66.4 kg K. Both fertilizers supplied supplemental sulfur (S), at 45 kg ha^{-1} (Patentkali) and 23.9 kg ha^{-1} (Kalisop). Non-fertilized treatments were the control. Both fertilizers have been approved for organic farming (Institute of Soil Science and Crop Cultivation 2017).

Table 3

Characteristics of mineral fertilizers used in field experiments

Mineral fertilizer	Nutrient content (%)		
	K	Mg	S
Patentkali	24.9	6.0	17.0
Kalisop	41.5	-	18.0

Seeds were not dressed, and protective sprays or organic fertilizers were not applied. Weeds were controlled by harrowing (twice in spring). The seeding rate was 350 kg spikelet ha^{-1}, and row spacing was 12.5 cm. Winter spelt was harvested with a combine harvester in the first 10 days of August.

Grain sampling

Winter spelt yields were determined after harvest. Representative spikelet samples of 100 g each were manually dehulled to determine pure grain yield (14% moisture content). Grain samples were collected according to International Seed Testing Association (ISTA) standards (International Seed Testing Association 2021).

Laboratory analyses

Thousand grain weight was determined on a laboratory weighing scale by weighing 100 kernels in 4 replications (International Seed Testing Association 2021). Grain samples were subjected to chemical analyses to determine the content of protein (N x 6.25), K, and Mg. Nitrogen content was determined using the Kjeldahl method – Kiel Flex K-360 (BUCHI, Switzerland). The concentrations of the following macronutrients were also determined: P (flow spectrophotometry) – UV – A280 (Shimadzu, Japan), K,and Ca (flame spectrometry emission) – Flame Photometer (BWB Technologies, The United Kingdom), Mg (atomic absorption spectrometry) – AA-6800 (Shimadzu, Japan).

Statistical analysis

The experimental data were processed statistically by ANOVA for randomized block designs (RBD) with the use of Statistica v. 12 software (StatSoft), separately for each location. Mean values were compared by the Tukey's HSD test. The significance level for all tests was set at $p \leq 0.05$.

RESULTS AND DISCUSSION

In the first experiment, where cv. Schwabenkorn was grown on medium-heavy soil, the average hulled and dehulled grain yield was 5.94 and 4.27 t ha^{-1}, respectively (Tables 4 and 5). Dehulled grain yields increased significantly after the application of mineral fertilizer containing K and Mg (Patentkali by 16.6%, and Kalisop by 10.2%) (Table 4). The respective values for hulled grain were 14.4% and 10.2%. Hulled grain yields ranged from 4.37 t ha^{-1} in 2007 to 7.14 t ha^{-1} in 2010. Winter spelt yields were significantly higher in 2009 and 2010 than in the remaining years of the experiment, which could be attributed to favorable weather conditions in these years, i.e. higher temperature and lower precipitation in the critical stages of plant growth and development relative to the long-term average. With the exception of 2008, the highest yields were noted in treatments supplied with K+Mg, followed by Kalisop. It should be noted that both fertilizers supplied supplemental S, which could have affected spelt yields. However, S levels in soil were moderate in both study sites; therefore, additional S had no signi-

Table 4

The impact of K and Mg mineral fertilization on the spikelet yields of winter spelt cv. Schwabenkorn grown on medium-heavy soil in Zgniłobłoty (2007-2010) and cv. Oberkulmer Rothkorn grown on heavy soil in Budziszewo (2011-2014), t ha^{-1}

Harvest year	Control	Patentkali	Kalisop	Mean for year
Schwabenkorn, medium-heavy soil				
2007	3.80 *j*	4.83 *h*	4.48 *i*	4.37 *C*
2008	5.02 *g*	5.53 *f*	5.45 *f*	5.33 *B*
2009	6.39 *e*	7.35 *ab*	7.02 *c*	6.92 *A*
2010	6.74 *d*	7.42 *a*	7.26 *ab*	7.14 *A*
Mean for fertilizer	5.49 *C*	6.28 *A*	6.05 *B*	
F (2; 24) = 730.7, p<0.01				
Oberkulmer Rothkorn, heavy soil				
2011	5.19 *de*	5.44 *c*	5.35 *cd*	5.33 *B*
2012	5.10 *e*	5.08 *e*	5.17 *de*	5.12 *B*
2013	6.04 *b*	6.37 *a*	6.41 *a*	6.27 *A*
2014	6.02 *b*	6.46 *a*	6.50 *a*	6.33 *A*
Mean for fertilizer	5.59 *B*	5.84 *A*	5.86 *A*	
F (2; 24) = 52.8, p<0.01				

[a], *b*, *c* … – homogenous groups for year x fertilizer interaction, *A*, *B*, *C* … – homogenous groups for years and fertilizers. Means with the same letter do not differ significantly from each other (Tukey's HSD test, $p \le 0.05$).

ficant influence on spelt development or yields. Sulphur deficiency is often the cause of retarded crop development and yield (Narayan et al. 2023). All K and Mg fertilizers that had been approved for organic farming in Poland at the time of the study contained S.

Cereals generally do not respond well to K fertilization, and the observed increase in yield was substantial, although there have also been large increases in yields under the influence of increased doses of potassium (Ali et al. 2019). Similar observations were made in this study, where the difference in yields did not exceed 10%. Winter spelt is a tall crop, and the cultivars grown in both experiments have long stems. As a result, straw and grain yields were high, which implies that the demand for K and Mg was also high. Greater differences in yield in response to K or Mg fertilization are very rarely noted, and they could occur on soils that are extremely deficient in these nutrients (Johnston et al. 2019). Positive responses to K fertilization have been reported in the literature; however, the reviewed studies were conducted on soils deficient in this nutrient (Chapman, Mason 1969, Arabi et al. 2002, Arif 2017, Tang et al. 2025).

In the second experiment, the average spelt yield was 5.76 t ha^{-1} for hulled grain and 4.20 t ha^{-1} for dehulled grain. Oberkulmer Rothkorn yields were somewhat lower than Schwabenkorn yields, but both cultivars responded similarly to mineral fertilization. These observations indicate that when winter spelt was grown on heavy soil (Oberkulmer Rothkorn), mineral fertilization with K and Mg (Patentkali) induced a similar increase in both hulled and dehulled grain yields, whereas the differences between fertilizers were not statistically significant (p<0.05).

According to most researchers, wheat responds positively to K fertilization, but in some studies, K fertilizers had no effect on wheat yields. In conditions of deficiency of available forms of potassium in the soil, this element can be released from soil reserves (Panda, Patra 2017, Richardson et al. 2024). In the conducted studies, such a phenomenon could have occurred, and this nutrient as absorbed from both exchangeable K and soil reserves (extracted in 1 mol dm^{-3} HNO_3).

Yield data were standardized, and different fertilization effects were compared to present the variations in yields across years (Figure 2). Standardized yields fluctuated in cycles between 2007 and 2014. In the first four years, when spelt was grown on medium-heavy soil, low yields in 2007 and 2008 were followed by higher yields in 2009 and 2010, and marked differences were observed between fertilized and control treatments. In the following four years, when spelt was grown on heavy soil, low yields in 2011 and 2012 were followed by higher yields in 2013 and 2014, and yields were similar in fertilized and control treatments.

Fig. 2. Standardized yield of winter spelt in successive years of the study

Wheat fertilization with K and Mg may affect not only yields but also crop development and yield quality parameters. In the present study, the application of K+Mg to medium-heavy soil delayed spelt maturation by 8 days and, consequently, resulted in higher yields (Table 5). A similar effect was reported by Chapman and Mason (1969).

Table 5

The impact of K and Mg mineral fertilization on the dehulled grain yields of winter spelt cv. Schwabenkorn grown on medium-heavy soil in Zgniłobłoty (2007-2010) and cv. Oberkulmer Rothkorn grown on heavy soil in Budziszewo (2011-2014), t ha^{-1}

Harvest year	Control	zPatentkali	Kalisop	Mean for year
Schwabenkorn, medium-heavy soil				
2007	2.62 *j*	3.42 *h*	3.10 *i*	3.05 *B*
2008	3.60 *gh*	4.01 *f*	3.76 *g*	3.79 *B*
2009	4.62 *e*	5.39 *a*	5.07 *b*	5.03 *A*
2010	4.85 *d*	5.48 *a*	5.36 *a*	5.23 *A*
Mean for fertilizer	3.92 *C*	4.57 *A*	4.32 *B*	
	F (2; 24) = 287.2, p<0.01			
Oberkulmer Rothkorn, heavy soil				
2011	3.76 *de*	3.97 *c*	3.91 *cd*	3.88 *B*
2012	3.70 *e*	3.71 *e*	3.77 *de*	3.73 *B*
2013	4.38 *b*	4.65 *a*	4.68 *a*	4.57 *A*
2014	4.37 *b*	4.72 *a*	4.75 *a*	4.61 *A*
Mean for fertilizer	4.05 *B*	4.26 *A*	4.28 *A*	
	F (2; 24) = 66.4, p<0.01			

a, *b*, *c*, … – homogenous groups for year x fertilizer interaction, *A*, *B*, *C*, … – homogenous groups for years and fertilizers. Means with the same letter do not differ significantly from each other (Tukey's HSD test, $p \leq 0.05$).

The TGW of spelt grown on medium-heavy soil fertilized with K+Mg was 4.2% higher than in the control treatment (Table 6). Numerous authors have reported on the positive effect of K fertilization on cereal crops (Chapman, Mason 1969, Arabi et al. 2002, Ralcewicz et al. 2009, Anaç et al. 2014, Arif 2017, Richardson et al. 2024). Ralcewicz et al. (2009) and Ceylan et al. (2016) found that Mg fertilization increased both wheat yields and TGW. In the current study, the protein content of grain from unfertilized plots was 116.8 mg kg^{-1}, and it was significantly higher in grain from plots fertilized with K and Mg (by 11.3%) and plots fertilized with K (by 8.6%). Flour obtained from high-protein grain is characterized by higher baking quality (the main factor affecting loaf volume). In other studies, K fertilizers also increased the pro-

Table 6

The impact of K and Mg mineral fertilization on selected parameters of winter spelt cv. Schwabenkorn grown on medium-heavy soil in Zgniłobłoty (2007-2010) and cv. Oberkulmer Rothkorn grown on heavy soil in Budziszewo (2011-2014), t ha^{-1}

Specification	Mineral fertilization			Mean
	control	Patentkali	Kalisop	
Schwabenkorn, medium-heavy soil (2007-2010)				
Maturity (days)	302 *b*	310 *a*	304 *b*	305.33
TGW (g)	45.04 *a*	46.92 *b*	45.11 *a*	45.69
Ingredient content (g kg^{-1})				
Crude protein	116.85 *b*	130.03 *a*	126.95 *a*	124.61
P	4.53 *a*	4.55 *a*	4.52 *a*	4.53
K	5.65 *a*	5.63 *a*	5.67 *a*	5.65
Mg	1.44 *b*	1.63 *a*	1.46 *b*	1.51
Ca	0.12 *a*	0.11 *a*	0.13 *a*	0.12
Oberkulmer Rothkorn, heavy soil (2011-2014)				
Maturity (days)	312 *a*	312*a*	312 *a*	312.00
TGW (g)	51.88 *a*	52.02 *a*	51.96 *a*	51.95
Ingredient content, mg kg^{-1}				
Crude protein	114.72 *a*	114.84 *a*	114.58 *a*	114.71
P	4.78 *a*	4.83 *a*	4.85 *a*	4.82
K	5.75 *a*	5.64 *a*	5.77 *a*	5.72
Mg	1.54 *a*	1.56 *a*	1.53 *a*	1.54
Ca	0.11 *a*	0.12 *a*	0.10 *a*	0.11

a, *b*, *c* – homogenous groups for significant comparisons. Means with the same letter do not differ significantly from each other (Tukey's HSD test, $p \leq 0.05$).

tein content of grain (Anaç et al. 2014, Messaoudi et al. 2023, Zang et al. 2024), but contrary results were also reported (Brennan, Bolland 2009, Gaj et al. 2013, Gaj, Górski 2014).

In the experiment conducted on medium-heavy soil, the Mg content of grain was significantly higher in treatments fertilized with K+Mg (Table 6). This is desirable because Mg delivers health benefits for consumers. According to Brodowska et al. (2017), Mg deficiency in soil decreases the content of this macronutrient in the entire plant, including grain. Gaj and Gorski (2014) also reported an increase in Mg and K concentrations in wheat grain in treatments fertilized with these macronutrients.

In the experiment conducted on heavy soil, TGW and the protein content of grain did not differ between treatments fertilized with K+Mg and the unfertilized control treatment.

CONCLUSIONS

In the experiment established on medium-heavy soil, the average yield of hulled and dehulled spelt grain cv. Schwabenkorn reached 5.92 and 4.27 t ha^{-1}, respectively. In comparison with the control treatment, mineral fertilization of spelt with Patentkali significantly increased dehulled grain yield by 16.6%, and fertilization with Kalisop increased yield by 10.2%. The corresponding increase in hulled grain yield was 14.4% and 10.2%, respectively. Supplementary mineral fertilization with Patentkali delayed crop maturation. In treatments fertilized with K and Mg, spelt grain was characterized by higher TGW (by 4.2%) and higher protein content (by 11.3%). In treatments fertilized with K and S only (without Mg), spelt grain had significantly higher protein content (by 8.6%), but Mg concentration increased significantly only in response to fertilization with K+Mg.

In the experiment established on heavy soil, the average yield of hulled and dehulled spelt grain cv. Oberkulmer Rothkorn reached 5.76 and 4.20 t ha^{-1}, respectively. Mineral fertilization with Patentkali and Kalisop significantly increased dehulled grain yields. Protein content and mineral concentrations in grain did not differ significantly between treatments fertilized with K+Mg and the unfertilized control treatment.

Author contributions

Conceptualization – JT, SS, methodology – JT, SS, KŻ-G, validation – SS, KT, MM, investigation – JT, KŻ-G, KT, data handling – KT, writing original draft – JT, SS, writing, review and editing – KT, JT, SS, visualization – JG, statistical analyses and result interpretation – JG, supervision – JT, SS, project administration – JT, funding acquisition – JT, MM. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no competing interests.

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