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The effect of soil tillage and sulphur fertilisation on content and ratios of macronutrients in the grain of spring triticale

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Abstract: The aim of the experiment was to determine the yield, content and uptake of macronutrients and their ratio in spring triticale, Milewo cultivar. The field experiment was conducted in the years 2014–2016 on Cambisols. The first experimental factor was a system of soil tillage (traditional (TRD) and reduced (RED)), and the second was sulphur fertilisation (0, 25 and 50 kg S/ha). Based on the study, it was found that the application of conventional tillage and the addition of sulphur fertilisation to NPK significantly increased spring triticale grain yield. The application of reduced tillage positively affected the increase in content and uptake in grain dry matter (DM) of N, S, P, K, Mg and Ca. Adding sulphur (S) to NPK fertilisation favourably increased the content and uptake of N, S, Mg, and Ca and did not affect the content of P and K. The application of reduced tillage expanded the ionic ratio of N:S, P:S while it narrowed the N:P ratio. However, the tillage system did not affect the ionic ratios Ca:P, K:Mg, K:(Ca + Mg) and molar K:(Ca + Mg). Adding sulphur to NPK fertilisation narrowed the N:S and P:S ratios while expanding the N:P and Ca:P ratios. Weather conditions during the 2016 growing season (relatively dry, k = 1.71) favoured spring triticale yield and uptake with dry grain weight of N, S, P, Mg and Ca. The highest N, S, P, K and Ca content in grain dry matter was shown in the 2014 season (relatively humid, k = 1.96). Numerous correlations were found between grain yield and the content, uptake and reciprocal ratios of elements in grain.

Keywords: *Triticosecale* Wittm. ex A. Camus.; mineral fertilisation; cereal; chemical composition

Triticale is a synthetic hybrid of wheat and rye (*Triticosecale* Wittm. ex A. Camus or *Triticale* A. Müntzing) (Stace 1987). In the world, the cultivation of spring triticale predominates, while in Europe, winter triticale cultivars. The area sown to triticale in Poland in 2023 was 1 201 000 ha, the grain harvest was 5 282 3000 t and the mean yield was 4.398 t/ha. In the EU-27, the area sown to triticale in 2023 was 2 551 000 ha, the grain yield was 10 873 000 tonnes, and the mean yield was 42.63 dt/ha. Poland is therefore the leader in triticale production in the EU and the world. In the EU-27, domestic triticale production accounts for 48.6%, while in the world, it accounts for 38.3% (FAO 2025). The triticale is essentially a feed cereal. Yet the area of its crops is correspondingly large, mainly in Europe, Northern America,

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Central Australia and New Zealand (Klikocka et al. 2019).

The content of macronutrients in grain is significantly influenced by soil and climatic conditions, mineral fertilisation and tillage methods (Kozera et al. 2023, Grzebisz et al. 2024, Grzebisz and Potarzycki 2025). Previous studies indicate, among other things, the significant influence of fertilisation (Bulut et al. 2022) and soil tillage methods (Dolijanović et al. 2019, 2022).

Soil tillage methods are an important factor in cereal production. It is well known that long-term reduced tillage and direct sowing are not recommended (Woźniak 2024). The above-mentioned methods of tillage deteriorate soil density and unfavourable distribution of nutrients in the soil profile. This, in turn, affects their uptake by plant roots and, consequently, affects plant yield and quality (Stankowski et al. 2016).

Supplementing the basic NPK fertilisation with sulphur is now becoming very important, which, through the soil and air deficit, reduces cereals' yield and quality (Klikocka and Marks 2018). Appropriately selected application rates of sulphur fertilisers are particularly important in the case of intensive nitrogen fertilisation because sulphur increases the utilisation of nitrogen (Podleśna et al. 2018). Sulphur additives for NPK fertilisation have been shown to increase the macronutrient content of cereals (Barczak and Nowak 2013, Klikocka et al. 2018). Sulphur deficiency in soils in several parts of the world has led to the use of sulphur fertiliser to enhance the production and quality of crops (Klikocka et al. 2015, 2022).

Research shows that soil tillage systems and sulphur deficiency reduce yield and quality, such as the content of nutrients. Therefore, this conclusion leads to the formulation of the following working hypothesis: conventional soil tillage and sulphur additive in the production of spring triticale increase the grain yield and improve the ionic ratios in the grain, which indirectly affects human and animal health (Kamanova et al. 2023). A three-year field study was conducted to verify this hypothesis and analyse the yield, content, and ionic ratio of macronutrients in spring triticale, Milewo cultivar. The first study factor was a soil tillage system, and the second was sulphur fertilisation.

At present, there is no information on the influence of soil tillage and the addition of sulphur to NPK fertilisation on the nitrogen (N), sulphur (S), phosphorus (P), potassium (K), magnesium (Mg) and calcium (Ca) content and uptake and value of ionic ratios in the grain of spring triticale. Therefore, in the presented field studies, the significance and role of soil tillage and sulphur fertilisers for spring rye grown on Cambisols were analysed (Ditzler et al. 2017)

MATERIAL AND METHODS

Field experiment. The three-year field experiment was realised in Malice, municipality Werbkowice near Hrubieszów (north longitude 50°42'N, east longitude 23°45'E). This subregion, known as the Hrubieszów Basin, is located in the southern part of the Lublin Voivodeship in the Zamojszczyzna region. The geological cover of the region is largely made up of loess and loess formations, except the south-eastern part (the Biłgoraj Plain and the Tarnogród Plateau), where lighter and agriculturally weaker soils made of poorly loamy and loose sands predominate (Kern et al. 1990).

The experiment was set up on Cambisols (Ditzler et al. 2017) consisting of light silty sand (sand 68%, silt 31%, clay 1%), classified as sandy loam. The characteristics of the soil of the experimental field were presented in Table 1, according to accepted methods (Ostrowska et al. 1991, Bloem et al. 2002).

The field experiment was set up using the split-plot method. It analysed the effect of 2 soil tillage systems and 3 doses of sulphur fertilisation on the reaction of spring triticale of the Milewo cultivar. The experiment was carried out in 4 replicates.

(I) Soil tillage systems: TRD – traditional (in autumn: harrowing (5 cm), pre-winter ploughing (20 cm). In spring: cultivating (15 cm), harrowing (5 cm); RED – reduced tillage (in autumn: harrowing (5 cm), cultivating (15 cm). In spring: cultivating (15 cm), harrowing (5 cm).

(II) Sulphur fertilisation rates (kg/ha): 0 (control), 25 and 50, as ammonium sulphate (104 and 208 kg/ha $(NH_4)_2SO_4$, respectively.

The plots' area was 30 m^2 (5 m × 6 m), and the harvest was 19.5 m^2. The spring triticale Milewo crop was potatoes (Mila), fertilised with cattle manure at a dose of 30 t/ha.

Before sowing in the third decade of March, spring triticale was brought in phosphorus fertilisers (triple superphosphate at the dose of 39.6 kg P/ha) and potassium fertilisers (potassium salt at the dose of 83 kg K/ha). Nitrogen fertilisers at a dose of 90 kg N/ha in the form of ammonium nitrate (partly ammonium sulphate) and sulphur fertilisers in the form of ammonium sulphate were applied at two dates, ½ dose

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Table 1. Chemical characteristics of soil (spring before sowing, layer 0–25 cm) (2014–2016)

Element	Unit	Types of soil analyses	2014	2015	2016
pH in 0.01 mol/L $CaCl_2$		the potentiometric method with a Methrohm 605 pH meter	5.6	5.8	5.7
C – total	(g/kg)	combustion with LECO EC-12®, model 752-100	9.1	9.0	8.7
N – total	(g/kg)	by Kjeldahl's method	0.9	0.9	0.8
P – available	(mg/kg)	colourimetric method – extracted in double-lactate extraction at pH 3.6 (1:50 *m*/*v*)	51.3	54.6	50.8
K – available	(mg/kg)	photometric method – extracted as P	85.6	84.3	81.2
Mg – available	(mg/kg)	AAS – extracted with 0.0125 mol/L $CaCl_2$	34.7	34.1	34.8
S – total	(mg/kg)	ICP-AES, mineralisation with HNO_3 + $Mg(NO_3)_2$	97.3	91.2	85.3
SO_4^{2-} – S available	(mg/kg)	ion-chromatography, extracted with 0.025 mol/L KCl	14.8	13.9	13.1

during soil preparation for sowing and ½ dose at the triticale stalk shooting stage (BBCH 30–31). During the vegetation, the plants were protected against pests by the recommendations adopted by the Institute of Plant Protection in Poznań (Horoszkiewicz-Janka et al. 2018).

Plant analysis and calculations. After crop harvest, grain yield in t/ha (at 11% moisture) was determined. Grain samples (from each plot) were dried at 60 °C for 48 h. They were then ground into particles smaller than 0.12 mm. Total nitrogen content was determined using the Kjeldahl method (Ostrowska et al. 1991). The content of total forms of sulphur, phosphorus, potassium, calcium and magnesium was determined using an ICP-OES (inductively coupled plasma optical emission spectrometry) spectroscope (Cygański 2014).

The total macronutrient contents were used to calculate their uptake in the plants. The calculation method and terminology were used according to Grzebisz (2009):

$$MU = M.C \times D.M.Y \quad (1)$$

where: MU – macronutrient uptake (kg/ha); MC – macronutrient content (g/kg DM); D.M.Y – dry matter yield (t/ha).

The content of macronutrients used for the calculation of the following ionic (mass) ratios: K:Ca, K:Mg, K:(Ca + Mg), Ca:P, Ca:Mg and mole ratios of K:(Ca + Mg):

$$IR = \frac{MC1}{MC2} \quad (2)$$

where: IR – the ionic (mass) ratio of macronutrients; MC1 – macronutrient content 1 (g/kg DM.); MC2 – macronutrient content 2 (g/kg DM).

$$MR = \frac{\frac{K}{19}}{\frac{Ca}{20} + \frac{Mg}{12}} \quad (3)$$

where: MR – mole ratio of K^+:(Ca + Mg); K – 19; Ca – 20; Mg – 12 – atomic numbers/mass of the elements.

Weather conditions. Weather conditions varied highly during the study period (2014–2016). To characterise them, the Sielianinov hydrothermal coefficient (*k*) was calculated following Skowera et al. (2014) for the spring triticale growing seasons, which fell between March and August. The individual seasons for plant vegetation were defined as: 2014 – fairly wet ($k = 1.96$), 2015 – dry bordering on fairly dry ($k = 0.98$) and 2016 – fairly wet bordering on optimal ($k = 1.71$) (Table 2). Overall, the year 2014 can be considered as wet. In 2015, only May was wet (91.1 mm), while June and August were dry (36.2 and 11.3 mm, respectively). In 2016, June and July were wet (116.8 and 115.3 mm, respectively), while June and August were characterised by an optimal rainfall distribution. Generally, in every month of the years analysed, the air temperature exceeded the average temperature of the multi-year period. However, it was not noticed that the distribution of precipitation and temperature significantly influenced the differentiation of developmental stages of spring triticale. However, the weather factor significantly influenced the yield of the plant and the content of macronutrients in the grain, as presented in the results section of the study.

According to Skowera et al. (2014), ranges of values of Sielianinov hydrothermal index were classified as follows: $k \leq 0.4$ – extremely dry; $0.4 < k \leq 0.7$ – very dry; $0.7 < k \leq 1.0$ – dry; $1.0 < k \leq 1.3$ – relatively dry; $1.3 < k \leq 1.6$ – optimal; $1.6 < k \leq 2.0$ – relatively humid; $2.0 < k \leq 2.5$ – humid; $2.5 < k \leq 3.0$ – very humid; $k > 3.0$ extremely humid.

Statistical analysis. Results were subjected to variance analysis with Snedecor's *F*-test. The significance of differences was analysed with the Tukey's test at the significance levels of $P = 0.05$ and 0.01.

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Table 2. Sums of rainfalls and mean air temperature and Sielianinov hydrothermal index during the spring triticale growing seasons in the years 2014–2016 and in the long-term period 1971–2011 (research station Zamość)

	Year	Month						Sum/mean
		III	IV	V	VI	VII	VIII	
Precipitation (mm)	2014	25.0	32.9	141.6	91.3	146.1	82.8	519.7
	2015	40.7	26.7	91.1	36.2	60.4	11.3	266.4
	2016	45.2	51.7	49.9	116.8	115.3	72.8	451.7
	1971–2011	26.3	42.3	65.1	78.3	94.3	61.3	367.5
Temperature (°C)	2014	6.0	10.3	14.2	16.3	20.7	18.7	2 646
	2015	5.1	8.6	13.6	17.7	21.1	22.3	2 713
	2016	4.8	10.2	14.3	18.9	19.7	18.2	2 639
	1971–2011	1.8	8.3	14.1	17.1	18.7	17.9	2 392
Sielianinov hydrotermal index (*k*)	2014	1.32	1.06	3.19	1.87	2.27	1.44	1.96
	2015	2.73	1.03	2.16	0.68	0.92	0.16	0.98
	2016	3.02	1.70	1.12	2.06	1.88	1.29	1.71
	1971–2011	4.85	1.70	1.48	1.53	1.62	1.11	1.54

Standard deviation and correlation coefficients were also calculated, and a posthoc analysis was performed (Trętowski and Wójcik 1991). The calculations were done using Excel 7.0 (Redmond, USA) and Statistica 12 software (StatSoft Inc., 2013).

RESULTS

Spring triticale yield of grain. The research factors applied in the field experiment, such as the tillage system and sulphur fertilisation rates, as well as the climatic conditions prevailing in the analysed growing seasons, mostly significantly influenced the studied traits. Spring triticale grain yield was significantly higher, by 5.65%, after conventional tillage compared to reduced tillage. A significant increase in grain yield was observed with increasing doses of sulphur fertilisation. The highest grain yield was recorded in the 2016 growing season, which was defined as relatively dry (k = 1.7). The significantly lowest grain yield was obtained in the 2014 growing season, which was defined as relatively humid (k = 1.96). The 2015 growing season was defined as dry (k = 0.98), and triticale yield in this season was significantly below that of the 2016 season but significantly above that of the 2014 season (Table 3).

Content and uptake of macronutrients. Triticale grain DM's nitrogen and sulphur content was significantly higher, by 4.8% and 1.5%, respectively, after reduced tillage compared to conventional tillage. As the sulphur dose increased, there was an increase in the N and S content of the grain. The most favourable nitrogen and sulphur content in DM of spring triticale grain was found in 2014 (relatively humid, k = 1.96). The least favourable for grain N content was the 2015 growing season (dry, k = 0.98), while for sulphur content, it was the 2016 growing season (relatively dry, k = 1.71). Nitrogen and sulphur uptake by DM of spring triticale grain was significantly higher after conventional tillage, by 4.8% and 4.2%, respectively, compared to reduced tillage. As the sulphur dose increased, N and S uptake by grain DM increased. The most favourable N and S uptake was in the 2016 growing season (relatively dry, k = 1.71). The least N and S uptake by grain DM was in the 2014 growing season (dry, k = 0.98) (Table 3). The phosphorus and potassium contents of grain were significantly higher after reduced tillage, by 6.85% and 7.8%, respectively, compared to conventional tillage. The application of sulphur fertilisation, irrespective of the applied dose, did not change the phosphorus and potassium content in the grain. The highest phosphorus content was found in the 2014 growing season (dry, k = 0.98) and of potassium in the 2015 and 2014 seasons. The least elements were contained in the dry weight of spring triticale grain in the 2016 growing season (relatively dry, k = 1.71). Phosphorus and potassium uptake in grain DM did not significantly depend on the tillage system used. Phosphorus uptake was significantly influenced by the application of medium and high doses of sulphur (25 and 50 kg S/ha, respectively), relative to the control object, without S additive).

Potassium uptake by dry weight of grain did not depend significantly on sulphur fertilisation, although

Table 3. The influence of soil tillage, sulphur (S) fertilisation and year of research on grain yield and content of nitrogen and sulphur in the spring triticale and their uptake

Factor/year		Grain yield (t/ha)	Nitrogen		Sulphur	
			content (g/kg DM)	uptake (kg/ha)	content (g/kg DM)	uptake (kg/ha)
Soil tillage	TRD	5.818 ± 0.082[a]	22.17 ± 0.26[b]	129.0 ± 0.3[a]	1.607 ± 0.006[b]	9.35 ± 0.10[a]
	RED	5.489 ± 0.103[b]	23.23 ± 0.26[a]	127.5 ± 0.4[a]	1.631 ± 0.006[a]	8.95 ± 0.10[b]
Sulphur	0 S	5.483 ± 0.085[c]	21.85 ± 0.42[c]	119.8 ± 4.2[c]	1.525 ± 0.047[c]	8.36 ± 0.39[c]
	25 S	5.661 ± 0.003[b]	22.40 ± 0.15[b]	126.8 ± 0.7[b]	1.607 ± 0.006[b]	9.10 ± 0.02[b]
	50 S	5.817 ± 0.081[a]	23.87 ± 0.58[a]	138.9 ± 5.3[a]	1.725 ± 0.053[a]	10.03 ± 0.44[a]
Year	2014	5.207 ± 0.223[c]	25.34 ± 1.35[a]	131.9 ± 1.8[b]	1.717 ± 0.049[a]	8.94 ± 0.10[b]
	2015	5.300 ± 0.177[b]	20.14 ± 1.28[c]	106.7 ± 10.8[c]	1.600 ± 0.009[b]	8.48 ± 0.33[c]
	2016	6.454 ± 0.400[a]	22.64 ± 0.03[b]	146.1 ± 8.9[a]	1.539 ± 0.040[c]	9.93 ± 0.39[a]
Mean		5.654	22.70	128.3	1.619	9.15

Soil tillage: TRD – traditional; RED – reduced. Different letters denote significant differences ($P \leq 0.05$) between the treatments. SD ± standard deviation; DM – dry matter

a trend can be observed that K uptake increases with an increase in S dose. Potassium uptake did not change significantly in the growing seasons studied. The most favourable phosphorus uptake was in the 2016 growing season (relatively dry, $k = 1.71$), while the least favourable was in the 2015 season (dry, $k = 0.98$) (Table 4). Magnesium and calcium contents in spring triticale grain were significantly higher after reduced tillage, by 5.4% and 5.7%, respectively, compared to conventional tillage (Table 5). For Mg content, both the medium (25 kg S/ha) and high (50 kg/ha) application rates resulted in a significant increase in the/this element in the grain, by 6.8% and 12.4%, respectively, compared to the control rate (without added S). In contrast, both medium and high doses of S influenced an equally favourable increase in Ca in grain. The most favourable effect on Mg content in grain had the weather distribution in the 2016 growing season (relatively dry, $k = 1.71$), while the least favourable effect was due to the moisture shortage in the 2015 season (dry, $k = 0.98$). Ca content in grain did not depend on weather conditions, although a favourable trend occurred in the 2014 growing season (relatively humid, $k = 1.96$). The uptake of magnesium, calcium, phosphorus, and potassium in the dry matter of the grain did

Table 4. The influence of soil tillage, sulphur (S) fertilisation and year of research on content of phosphorus and potassium in the spring triticale and their uptake

Factor/year		Phosphorus		Potassium	
		content (g/kg DM)	uptake (kg/ha)	content (g/kg DM)	uptake (kg/ha)
Soil tillage	TRD	3.800 ± 0.065[b]	22.11 ± 0.05[a]	5.579 ± 0.108[b]	32.46 ± 0.15[a]
	RED	4.059 ± 0.064[a]	22.28 ± 0.03[a]	6.014 ± 0.109[a]	33.01 ± 0.12[a]
Sulphur	0 S	3.982 ± 0.026[a]	21.85 ± 0.18[c]	5.567 ± 0.114[a]	30.52 ± 1.12[a]
	25 S	3.935 ± 0.002[a]	22.28 ± 0.03[b]	5.770 ± 0.013[a]	32.66 ± 0.05[a]
	50 S	3.962 ± 0.016[a]	23.05 ± 0.41[a]	6.053 ± 0.128[a]	35.21 ± 1.22[a]
Year	2014	4.277 ± 0.173[a]	22.27.3 ± 0.02[b]	5.967 ± 0.085[a]	31.07 ± 0.85[a]
	2015	3.819 ± 0.055[b]	20.24 ± 0.99[c]	6.263 ± 0.233[a]	33.19 ± 0.21[a]
	2016	3.693 ± 0.118[c]	23.82 ± 0.80[a]	5.158 ± 0.319[b]	33.29 ± 0.26[a]
Mean		3.930	22.22	5.796	32.77

Soil tillage: TRD – traditional; RED – reduced. Different letters denote significant differences ($P \leq 0.05$) between the treatments. SD ± standard deviation; DM – dry matter

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Table 5. The influence of soil tillage, sulphur (S) fertilisation and year of research on content of magnesium and calcium in the spring triticale and their uptake

Factor/year		Magnesium		Calcium	
		content (g/kg DM)	uptake (kg/ha)	content (g/kg DM)	uptake (kg/ha)
Soil tillage	TRD	1.121 ± 0.015^{b}	6.52 ± 0.01^{a}	0.698 ± 0.010^{b}	4.06 ± 0.00^{a}
	RED	1.182 ± 0.015^{a}	6.49 ± 0.01^{a}	0.738 ± 0.010^{a}	4.05 ± 0.00^{a}
Sulphur	0 S	1.071 ± 0.040^{c}	5.87 ± 0.32^{c}	0.665 ± 0.026^{b}	3.65 ± 0.20^{c}
	25 S	1.144 ± 0.004^{b}	6.48 ± 0.01^{b}	0.721 ± 0.001^{a}	4.08 ± 0.01^{b}
	50 S	1.240 ± 0.044^{a}	7.21 ± 0.35^{a}	0.768 ± 0.025^{a}	4.47 ± 0.20^{a}
Year	2014	1.170 ± 0.009^{b}	6.09 ± 0.21^{b}	0.721 ± 0.001^{a}	3.75 ± 0.15^{b}
	2015	0.906 ± 0.123^{c}	4.80 ± 0.85^{c}	0.714 ± 0.002^{a}	3.78 ± 0.14^{b}
	2016	1.380 ± 0.114^{a}	8.91 ± 1.20^{a}	0.718 ± 0.000^{a}	4.63 ± 0.28^{a}
Mean		1.152	6.51	0.718	4.06

Soil tillage: TRD – traditional; RED – reduced. Different letters denote significant differences ($P \leq 0.05$) between the treatments. SD ± standard deviation; DM – dry matter

not depend significantly on the tillage system used. The uptake of Mg and Ca in grain DM increased significantly with the increase in S dose. The most favourable growing season for Mg and Ca uptake was 2016 (relatively dry, k = 1.71) (Table 5).

The application of reduced tillage positively increased the content and uptake in DM of N, S, K, Mg and Ca. Adding sulphur to NPK fertilisation favourably increased the content, and the uptake of N, S, Mg, and Ca did not affect the content of P and K. The grain yield and uptake with grain DM of nitrogen, sulphur, phosphorus, magnesium and calcium were most positively affected by the 2016 growing season (relatively dry, k = 1.71). The highest N, S, P, K and Ca content in grain DM was shown in the 2014 season (relatively humid, k = 1.96).

Numerous positive correlations were found between spring triticale grain yield and element content and uptake. No significant correlation was found between grain yield and grain content of nitrogen, sulphur, and calcium, as well as between grain yield and grain uptake of potassium. The content of phosphorus and calcium in grain formed the fewest correlations with other elements. The others formed numerous correlations with each other (Table 6).

Ionic ratios. The elemental ratios in spring triticale grain are an essential characteristic for determining yield quality. N:S and P:S ratios were wider after reduced tillage compared to conventional tillage, by 3.0% and 5.6%, respectively. The widest ratio of N:S and P:S was in the control object (without S); the addition of sulphur caused a significant narrowing of the ratios. A significant narrowing of the N:S ratio was recorded in the 2015 growing season (dry, k = 0.98), for the ratio of P:S ratio was not found to be significantly influenced by weather conditions in individual growing seasons. A significant narrowing of the N:P ratio, by 2.4%, occurred after applying reduced tillage compared to conventional tillage. The application of the highest sulphur rate (50 kg S/ha) expanded the N:P ratio significantly concerning the lower S rate (25 kg S/ha) and the control (without S). The significant expansion of the N:P ratio was influenced by the 2016 growing season (relatively dry, k = 1.71) and the 2014 season (relatively humid, k = 1.96). The Ca:P ratio in spring triticale grain DM did not significantly depend on the tillage system (ST) used. However, it expanded significantly with increasing sulphur dose. A significant expansion of the ratio compared to the 2014 season (relatively humid, k = 1.96) occurred in the 2016 season (relatively dry, k = 1.71) and the 2014 season (dry, k = 0.98) (Table 7). The applied tillage system and the addition of sulphur to NPK fertilisation did not affect the ionic ratios of K:Ca, K:Mg, K:(Ca + Mg), Ca:P, Ca:Mg) and molar (equivalent) K:(Ca + Mg). However, a trend can be observed that after applying the highest sulphur dose (50 kg S/ha), all the mentioned ratios narrowed. Also, the application of reduced tillage slightly affected the expansion of the ion ratios K:Ca, K:Mg, K:(Ca + Mg) and the mole ratio K:(Ca + Mg). The widening of the ratios of the elements in question was most affected by the 2015 growing season (dry, k = 0.98), while the 2016 growing season significantly affected their narrowing (relatively dry, k = 1.71) (Table 8).

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Table 6. Correlation coefficients between grain yield and content and uptake of macroelements by grain dry matter of spring triticale

Features (n = 18)		No.	2	3	4	5	6	7	8	9	10	11	12	13
Grain yield		1	–0.050	**0.720**	–0.301	**0.685**	**–0.636**	**0.700**	**–0.733**	0.350	**0.713**	**0.888**	0.035	**0.777**
N	content	2	–	**0.656**	**0.563**	0.350	**0.734**	**0.585**	0.053	0.016	**0.522**	0.321	0.334	0.153
	uptake	3	–	–	0.171	**0.768**	0.027	**0.933**	**–0.505**	0.292	**0.929**	**0.898**	0.277	**0.705**
S	content	4	–	–	–	**0.484**	**0.508**	0.059	**0.577**	0.398	0.055	–0.096	**0.689**	0.192
	uptake	5	–	–	–	–	–0.228	**0.654**	–0.215	**0.646**	**0.686**	**0.736**	**0.582**	**0.875**
P	content	6	–	–	–	–	–	0.101	**0.515**	–0.149	–0.025	–0.305	0.204	–0.372
	uptake	7	–	–	–	–	–	–	–0.453	0.339	**0.887**	**0.856**	0.245	**0.664**
K	content	8	–	–	–	–	–	–	–	0.377	**–0.541**	**–0.665**	0.457	–0.274
	uptake	9	–	–	–	–	–	–	–	–	0.238	0.301	**0.711**	**0.702**
Mg	content	10	–	–	–	–	–	–	–	–	–	**0.954**	0.340	**0.750**
	uptake	11	–	–	–	–	–	–	–	–	–	–	0.244	**0.824**
Ca	content	12	–	–	–	–	–	–	–	–	–	–	–	**0.655**
	uptake	13	–	–	–	–	–	–	–	–	–	–	–	–

Bold letters represent significant differences at $P_{0.05} \geq 0.468$; $P_{0.01} \geq 0.590$

A significantly positive correlation was observed between grain yield and the ratio in grain N:P and Ca:P. The other ratios, except for N:S and P:S, correlated significantly positively with grain yield. Non-significant correlations were found between P:S and Ca:P and the other ratios. Most of the ratios correlated with each other (Table 9).

DISCUSSION

The effect of soil tillage and sulphur fertilisation on grain yield. The research is based on a three-year field experiment on the application of traditional and reduced tillage and the addition of sulphur fertilisation in the amount of 25 and 50 kg/ha to basic NPK fertilisation in spring triticale cultivation under the climatic and soil conditions of Zamojszczyzna region, revealed a number of significant differences. It was shown that applying full conventional tillage and using the plough (TRD) favourably affects spring triticale grain yield. Reduced tillage (replacing plough tillage with a cultivator) leads to a 5.65% decrease in grain yield. Woźniak and Stępniowska (2017) and Panasiewicz et al. (2020) reported that

Table 7. The influence of soil tillage, sulphur (S) fertilisation and year of research on the ratios of macroelements in the grain of spring triticale

Factor/year		N:S	N:P	P:S	Ca:P
		(mass)			
Soil tillage	TRD	13.80 ± 0.11[b]	5.834 ± 0.029[a]	2.365 ± 0.031[b]	0.184 ± 0.001[a]
	RED	14.24 ± 0.11[a]	5.723 ± 0.026[b]	2.489 ± 0.031[a]	0.182 ± 0.001[a]
Sulphur	0 S	14.33 ± 0.16[a]	5.483 ± 0.146[b]	2.613 ± 0.093[a]	0.167 ± 0.008[c]
	25 S	13.94 ± 0.04[b]	5.693 ± 0.041[b]	2.449 ± 0.011[b]	0.183 ± 0.000[b]
	50 S	13.84 ± 0.09[b]	6.025 ± 0.124[a]	2.297 ± 0.065[c]	0.194 ± 0.005[a]
Year	2014	14.76 ± 0.37[a]	5.925 ± 0.074[b]	2.491 ± 0.032[a]	0.169 ± 0.007[c]
	2015	12.59 ± 0.72[b]	5.274 ± 0.251[c]	2.387 ± 0.002[a]	0.187 ± 0.002[b]
	2016	14.71 ± 0.34[a]	6.131 ± 0.177[a]	2.400 ± 0.013[a]	0.194 ± 0.006[a]
Mean		14.02	5.778	2.427	0.183

Soil tillage: TRD – traditional; RED – reduced. Different letters denote significant differences ($P \leq 0.05$) between the treatments. SD ± standard deviation

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Table 8. The influence of soil tillage, sulphur (S) fertilisation and year of research on the ratios of macroelements in the grain of spring triticale

Factor/year		K:Ca	K:Mg	K:(Ca + Mg)		Ca:Mg
		(mass)		(mass)	(mole)	(mass)
Soil tillage	TRD	7.993 ± 0.039[a]	4.977 ± 0.027[a]	3.067 ± 0.016[a]	2.288 ± 0.012[a]	0.623 ± 0.000[a]
	RED	8.149 ± 0.038[a]	5.088 ± 0.028[a]	3.132 ± 0.016[a]	2.338 ± 0.012[a]	0.624 ± 0.000[a]
Sulphur	0 S	8.371 ± 0.149[a]	5.198 ± 0.083[a]	3.207 ± 0.054[a]	2.392 ± 0.039[a]	0.621 ± 0.001[a]
	25 S	8.003 ± 0.034[a]	5.044 ± 0.006[a]	3.094 ± 0.002[a]	2.311 ± 0.001[a]	0.630 ± 0.003[a]
	50 S	7.882 ± 0.095[a]	4.881 ± 0.075[a]	3.014 ± 0.042[a]	2.248 ± 0.032[a]	0.619 ± 0.002[a]
Year	2014	8.276 ± 0.102[a]	5.100 ± 0.034[b]	3.155 ± 0.028[b]	2.352 ± 0.019[b]	0.616 ± 0.003[b]
	2015	8.772 ± 0.350[a]	6.913 ± 0.941[a]	3.866 ± 0.383[a]	2.964 ± 0.322[a]	0.788 ± 0.082[a]
	2016	7.184 ± 0.444[a]	3.738 ± 0.645[c]	2.459 ± 0.180[c]	1.799 ± 0.2257[c]	0.520 ± 0.051[c]
Mean		8.071	5.032	3.099	2.313	0.643

Soil tillage: TRD – traditional; RED – reduced. Different letters denote significant differences ($P \leq 0.05$) between the treatments. SD ± standard deviation

the used tillage systems significantly affect the grain yield of cereals. However, there are reports in the literature on the different effects of conventional and no-ploughing tillage systems on cereal yields. Several authors claim that non-inversion tillage does not affect the yield of cereals (Golik et al. 2005, Rusu et al. 2006, Małecka et al. 2015). Others have shown decreased cereal yield under no-ploughing tillage (Jug et al. 2011, Klikocka et al. 2019). Other studies have shown reduced and no-tillage systems increased cereal yield (Kosutic et al. 2005, De Vita et al. 2007). Martinez et al. (2016) claim that winter cereals' crop yield was significantly higher with non-soil tillage use. Jaśkiewicz (2019) claim that N, P and Mg concentrations did not depend on the soil tillage system. At the same time, the author noted that higher concentrations of potassium, calcium and sodium were found under ploughing conditions.

In the presented experiment, it was shown that the addition of sulphur to the basic NPK fertilisation significantly increases spring triticale grain yield. Podleśna (2013) reported that adding 60 kg S/ha increased winter wheat grain yield by 11%. Similarly, Podleśna et al. (2018) found that the addition of sulphur has also an effect on spring rye yield. The opinion about the positive yield-forming effect of sulphur on spring wheat yield was also described by the studies of Gondek and Gondek (2010), Klikocka et al. (2018) and Klikocka and Marks (2018).

Macronutrient content and uptake. As shown in this research, the application of reduced tillage favoured the increase in the content and uptake in

Table 9. Correlation coefficients between grain yield and ratio of macroelements by grain dry matter of spring triticale

Features (n = 18)	No.	2	3	4	5	6	7	8	9	10
Grain yield	1	0.271	**0.634**	–0.239	**0.515**	**–0.815**	**–0.755**	**–0.798**	**–0.785**	**–0.678**
N:S mass	2	–	–0.138	**0.650**	**–0.472**	–0.334	**–0.708**	**–0.645**	**–0.667**	**–0.808**
N:P mass	3	–	–	**–0.542**	**0.827**	**–0.856**	**–0.484**	**–0.571**	**–0.541**	–0.270
P:S mass	4	–	–	–	**–0.736**	0.284	–0.053	0.009	–0.013	–0.203
Ca:P mass	5	–	–	–	–	**–0.556**	–0.155	–0.241	–0.212	0.028
K:Ca mass	6	–	–	–	–	–	**0.864**	**0.912**	**0.897**	**0.722**
K:Mg mass	7	–	–	–	–	–	–	**0.994**	**0.997**	**0.971**
K:(Ca + Mg) mass	8	–	–	–	–	–	–	–	**0.999**	**0.941**
K:(Ca + Mg) mole	9	–	–	–	–	–	–	–	–	**0.953**
Ca:Mg mass	10	–	–	–	–	–	–	–	–	–

Bold letters represent significant differences at $P_{0.05} \geq 0.468$; $P_{0.01} \geq 0.590$

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dry matter of spring triticale grain of macroelements. In the research of Kozera et al. (2023), ploughing and shallow tillage methods generally did not differentiate the content of mineral components (P, Ca and Mg) in the grain of the wheat cultivars. However, Dolijanovic et al. (2019, 2022) claim that the contents of the nutrients in the wheat grain are significantly higher under chisel ploughing. Woźniak and Stępniowska (2017) showed that the conventional system enhanced the content of phytate-P and iron, and the reduced system positively influenced the content of Ca and Mg. In contrast, the herbicide (HT) system positively stimulated the content of P, K, Mg and Cu in grains of wheat. According to Kwiatkowski et al. (2022), plough tillage increased the nitrogen (about 16%) and potassium content (about 17%) in spring wheat grain in the conservation tillage system. However, the content of Ma and Ca in spring wheat grain was higher under conservation tillage conditions than plough tillage.

Our research showed that adding sulphur to NPK fertilisation favourably increased the content and uptake of nitrogen, sulphur, magnesium, and calcium and had no effect on phosphorus and potassium content. Similar results were obtained in another study by Klikocka et al. (2018, 2022). The opposite results were obtained in the experiments of Barczak and Nowak (2013), who used sulphur to fertilise oats. They showed a noticeable decrease in the grain's P, K and Ca content. Also, Skwierawska et al. (2008) claim that the complement of sulphur to NPK fertilisers has no effect on the P and K accumulation in the dry matter of spring barley grain. Gondek and Gondek (2010) did not show statistically significant differences in the Mg content in wheat grain subjected to NPK fertilisation supplemented with sulphur.

In the present study, the growing seasons of 2014–2016 influenced the traits studied. The 2016 growing season (relatively dry, k = 1.71) had the most favourable effect on triticale grain yield and uptake with grain dry matter of nitrogen, sulphur, phosphorus, magnesium and calcium. However, the highest N, S, P, K and Ca content in grain dry matter was shown in the 2014 season (relatively humid, k = 1.96). According to De Vita et al. (2007), in conditions with low sums of precipitation, more advantageous yields of cereals are reported in the no-tillage system than in the traditional tillage system. In turn, Zikeli et al. (2013) demonstrated that higher yields of durum wheat were determined in the traditional than in the simplified tillage system in years with high precipitation. In an experiment conducted by Woźniak and Makarski (2013), grain from conventional tillage was characterised by a more advantageous potassium, magnesium and manganese content. As reported by Klikocka et al. (2018), the lowest macronutrient uptake by spring wheat, cultivated in the 2010 growing season, proves the occurrence of unfavourable weather conditions from shooting to heading, when nutrient uptake and growth processes are the most intense. Jaśkiewicz (2019) claims that the highest accumulation of Mg and P was found in the season with the highest precipitation. Also, the concentration of N and Na in triticale grain was more advantageous in the season with lower precipitation. Also, in her spring triticale study, Rzążewska (2023) stated that P, K, Mg, Ca and Na content changed in study seasons due to weather conditions.

The analysis of variance carried out for grain yield, dry matter content and uptake by dry matter of N, P, K, S, Mg and Ca did not show a significant interaction between the factors used in the experiment. However, although not statistically confirmed, it can be seen that grain yield and uptake by DM of grain increased proportionally against tillage after sulphur addition. This type of effect of the yield factor, in this case, fertiliser, signals an additive effect of sulphur and tillage due to the summation of the applied components. In general, the additive action of the components is revealed when there is a constant indicative increase in weight (yield) following the application of the second factor.

In the presented study, numerous correlations were shown between grain yield and element content and uptake. Only a significant correlation was not shown between grain yield and the content of nitrogen, sulphur and calcium in grain, as well as between grain yield and uptake of potassium by grain. The content of phosphorus and calcium in grain formed the fewest correlations with the other elements. The others correlated with each other in large numbers.

Klikocka et al. (2022) showed significant positive correlations between the wheat grain yield as well as the content and uptake of K, Mg and Ca by grain. The correlation coefficients between triticale grain yield and the content of macronutrients decreased in the order Mg > Ca > N > S > P > K. However, the strength of the relationship between grain yield and uptake of macroelements by grain DM had the following order: Mg > Ca > N > P > S > K. Cakmak (2002) claims that plants with low yields contain more elements per unit of plant mass about plants

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with high yields, regardless to the nutrient content in the soil. This situation is referred to as the concentration-dilution phenomenon.

Ionic ratio. As shown in the presented study, the application of reduced tillage expanded the ionic ratio of N:S and P:S, while it narrowed the N:P ratio. However, the tillage system did not affect the ionic ratios Ca:P, K:Mg, K:(Ca + Mg) and molar K:(Ca + Mg). The value of nutrient ratios is similar to the study of Kozera et al. (2017). Ion or mole ratios of macronutrients are an essential characteristic of crop yield quality. Jankowska-Huflejt's et al. (2009) study shows that the surplus of K is more often reported in animal feed than its deficit. Jarnuszewski and Meller (2013) state that the balance between uni- and bivalent ions influences the more advantageous content of Ca and Mg, which may be antagonistic to the K. As shown in this experiment, soil tillage and S fertilisation affected the increase of content and uptake in the grain of Mg and Ca. The addition of sulphur to NPK fertilisation narrowed the ratio of N:S, P:S because the S content in the grain originating from these objects increased. At the same time, it widened the N:P and Ca:P ratios as P content in grain was not dependent on S fertilisation. In turn, sulphur treatment did not affect the ionic and molar ratio of K:(Ca + Mg). In another study, Klikocka et al. (2022) found that S addition widened K:Mg and K:(Ca + Mg) values. Yang et al. (2024) argue that the N:P ratio is the key factor restricting plant growth, which is connected with N and P uptake by plants. According to Sadras (2006), more than 40% of cereal plants obtain maximum yield at N:P ratio between 4 and 6, like in our experiment. As is well known, the metabolism of N and S is closely related (Hopkins 2015). The N to S ratio of proteins is considered a reliable indicator of the sulphur supply of plants. According to Podleśna (2013), the N:S ratio in wheat grain proteins ranges from 12 to 25 and is changed by different amounts of N and S used in fertilisation. Later research with spring red wheat showed that grain S concentration lower than 1.5 g/kg DM. and grain N:S ratio higher than 13.3:1 indicate sulphur deficiency. However, it depends on N availability (Reussi et al. 2011). In the present experiment, the N:S ratio averaged 14.07 and depended significantly on the tillage and sulphur fertilisation used. Significant positive or negative correlations were found to occur between grain yield and the nutrient ratios studied. Only the ratios N:S and P:S did not correlate significantly with grain yield. As shown in the results section, the 2015 growing season (dry, k = 0.98) influenced the extension of the ratios. In contrast, the 2016 growing season significantly influenced their narrowing (relatively dry, k = 1.71). The results indicate that spring triticale responds significantly to the tillage system, sulphur fertilisation and weather conditions. Using conventional tillage and adding sulphur fertiliser to NPK significantly increased spring triticale grain yield. Therefore, the farmer should carefully recognise the cultivation technology of spring triticale and consider the climate and soil conditions.

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