

# Efficiency of Fertilization and Utilization of Nitrogen and Sulphur by Spring Wheat

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## Abstract

The aim of our study was to evaluate the effects of nitrogen (N) and sulphur (S) fertilizer on harvest index (HI), agronomic efficiency (AE), physiological efficiency (PE), utilization (U), and final efficiency index (EFI). We conducted a field experiment (2009-11) in southeastern Poland on Cambisols (WRB 2014). The experiment included two variables: N fertilization (0, 40, 80, and 120 kg/ha) and S fertilization (0 and 50 kg/ha).

The experiment showed the positive effect of N and S fertilization on grain and straw yields of spring wheat cv. Tybalt, with the highest yield obtained in the case of the application of 120 kg N ha<sup>-1</sup> (grain 5.59 t ha<sup>-1</sup>, straw 8.00 t ha<sup>-1</sup>). S fertilization increased grain yield by 3.58% and straw by 6.16%. Although N and S fertilization increased content and uptake of N and S in DM, they decreased significantly on the harvest index of N and S (HI<sub>N</sub>, HI<sub>S</sub>). On average, HI<sub>N</sub> was 76.41% and HI<sub>S</sub> was 45.87%. Among the tested combinations, the highest agronomic efficiency of N (AE<sub>N</sub>), agronomic efficiency of S (AE<sub>S</sub>), physiological efficiency of N (PE<sub>N</sub>), physiological efficiency of S (PE<sub>S</sub>), utilization of N (U<sub>N</sub>), and utilization of S (U<sub>S</sub>) as well the best final efficiency of N and S (EFI<sub>N</sub>, EFI<sub>S</sub>) were noted for the object where N application increased to 80 kg ha<sup>-1</sup> with the addition of 50 kg S ha<sup>-1</sup>. This combination should be recommended for use in the practice of spring wheat fertilization with N and S. Increasing the rate of N fertilizer to 120 kg ha<sup>-1</sup> caused a reduction in the utilization of N (U<sub>N</sub>), and the addition of S to this level of N caused a drop in its utilization by the grain. In conclusion, S fertilization is necessary in the conditions of negative S balance in the cultivated soils.

**Keywords:** nitrogen, S, utilization, spring wheat

## Introduction

A noticeable problem in agriculture around the world is the worsening S deficiency caused by an extreme tightening of environmental standards at the end of

the last century [1]. In Poland in 2010 as many as 94% of profiles tested were classified as low in S (<16.5 mg SO<sub>4</sub><sup>2-</sup> kg<sup>-1</sup> [2]. This situation raises the concern that the NPK fertilizer generally applied will not be balanced, and the S deficiency may reduce utilization of the remaining components, primarily N.

N and S are both important constituents of protein, and adequate supplies of both nutrients are important for optimum crop yield [3-4]. S and nitrogen nutrition interact

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at many levels, as the uptake and assimilation of  $\text{NO}_3$  and  $\text{SO}_4^{2-}$  have much in common, and there are many common products of N and S metabolism [5]. For assimilation of sulphate to occur, plants must contain adequate levels of this precursor, and as an amino acid its concentration is dependent on N nutrition [6]. An S deficiency in crop production can cause serious economic and ecological problems. Where S and magnesium are insufficient, the 'law of the minimum' may come into play, while intensive fertilization of crops with nitrogen can lead to a reduction in its utilization by plants [7]. This will affect the content of S and its primary and secondary metabolites, which play an important role in the diet and health of animals and humans [3].

The aim of our study was to evaluate the effects of spring wheat fertilization with N and S fertilizers on harvest index (HI), agronomic efficiency (AE), physiological efficiency (PE), utilization (U), and final efficiency index (EFI).

### Materials and Methods

A field experiment was carried out in 2009-11 in Malice in southeastern Poland (50°42' N, 23°15' E), in a randomized split-plot design with four replications. The experiment was conducted on cambisols (WRB 2014) consisting of light silty sand (sand 68%, silt 31%, clay 1%). The soil was slightly acidic (pH = 5.6), with high available P content (mean 52.1 mg kg<sup>-1</sup>), medium content of available K (mean 84.5 mg kg<sup>-1</sup>), and available Mg (mean 34.5 mg kg<sup>-1</sup>), and low content of available S-SO<sub>4</sub> (mean 12.4 mg kg<sup>-1</sup>).

The subject of the experiment was the Tybalt variety of spring wheat (*Triticum aestivum* L.) fertilized with different doses of N (0, 40, 80, and 120 kg N ha<sup>-1</sup>) and S (0 and 50 kg S ha<sup>-1</sup>). The area of each plot was 30 m<sup>2</sup> (5 m × 6 m). The first application of N (as 34% ammonium nitrate) at a rate of 40.0 kg N ha<sup>-1</sup> was made before sowing (between 28 March and 5 April, depending on the year). In the combination of 80 and 120 kg N ha<sup>-1</sup> the second N application was made during the beginning of shooting (BBCH 30-31). In the combination of 120 kg N ha<sup>-1</sup> the third N application was made during the heading (BBCH 55-59). The first dose of S was applied before sowing (40 kg S ha<sup>-1</sup>) in the form of kieserite  $\text{MgSO}_4 \times \text{H}_2\text{O}$  (as 15.1% Mg, 20.0 % S), and the second (10 kg S ha<sup>-1</sup>) as foliar application in the form of magnesium sulphate heptahydrate ( $\text{MgSO}_4 \times 7\text{H}_2\text{O}$ ) (10.2% Mg, 12.8% S or 32% SO<sub>3</sub>) (3.2% SO<sub>3</sub> solution in 100 L of water per 300 L water per ha) in the beginning of shooting (BBCH 30-31). Before sowing, in the dose 39.6 kg P ha<sup>-1</sup> (as 17.4% granular triple superphosphate) and K in the dose 83 kg K ha<sup>-1</sup> (as 49.8 % potassium salt) were applied. More detailed data on meteorological conditions and protection of the spring wheat plants against pests in the experimental stand can be found in Klikocka et al. [8].

Grain yield and straw (at 11% moisture content) was calculated after the harvest (BBCH 92) from each

plot. In dry matter (DM) of grain and straw the content of total N and total S (g kg<sup>-1</sup> DM) was determined with a LECO CNS-2000 analyser. Content of S was determined by infrared spectrometry (DIN ISO 15178:2001) and N in a differential thermal conductivity detector (DIN ISO 13878:1998). Nutrient uptake by the grain and straw was calculated as the product of the N and S content and grain and straw yield of spring wheat, respectively.

The efficiency of fertilization and utilization of nitrogen and S by the spring wheat was calculated for average samples as follows:

- A. Agronomic efficiency ( $\text{AE}_{\text{N or S}}$ ) expressed in kg/kg, which is the ratio of the increase in yield due to fertilization with N and S (yield at  $\text{N}_x$  – yield at  $\text{N}_0$ ) to the N and S fertilizer-applied  $\text{N}_x$
- B. Physiological efficiency ( $\text{PE}_{\text{N or S}}$ ) expressed in kg/kg, which is the ratio of the increase in yield due to fertilization with N and S (yield for  $\text{N}_x$  – yield for  $\text{N}_0$ ) to the increase in N and S accumulation (accumulation at  $\text{N}_x$  – accumulation at  $\text{N}_0$ )
- C. Utilization of N and S ( $\text{U}_{\text{N or S}}$ ) – expressed as a percentage, calculated from the quotient of agronomic efficiency divided by physiological efficiency
- D. Final efficiency index ( $\text{EFI}_{\text{N or S}}$ ) – expressed in PLN, which is the increase in yield in PLN per PLN spent on fertilizer
- E. Harvest index of N and S ( $\text{HI}_{\text{N or S}}$ ) – expressed as a percentage, the ratio of the amount of N or S in the wheat grain to the total amount of N or S in the plant.

Analysis of variance was performed by Snedecor's F-test. Significance of differences was calculated using Tukey's test ( $p = 0.05$ ) followed by *post-hoc* analysis. The statistical software Excel 7.0 and Statistica (StatSoft Polska'97) were used for analysis.

### Results and Discussion

Analysis of the results showed a significant beneficial effect of N and S fertilizer on the grain and straw yield of spring wheat and on most of the agro-economical characteristics. For grain yield and studied characteristics no interaction was found between increasing application rates of N and S. However, the addition of S to each dose of N independently increased yield and a number of other features. This type of yield-increasing factor, in this case fertilizer, signals the additive effect of S. This type of reaction is manifested in conditions in which the deficiency of the nutrient is small, which is consistent with the law of diminishing returns (also known as Mitscherlich's Law) [9].

The experiment showed a positive effect of N and S application on grain yield of spring wheat with the highest yield obtained in the case of the application of 80 kg N ha<sup>-1</sup> (5.40 t ha<sup>-1</sup>) and 120 kg N ha<sup>-1</sup> (5.59 t ha<sup>-1</sup>) – an increase in the average 1.42 t ha<sup>-1</sup> (34.7%) with respect to the control. This is consistent in accordance with observations of Ercoli et al. [10].

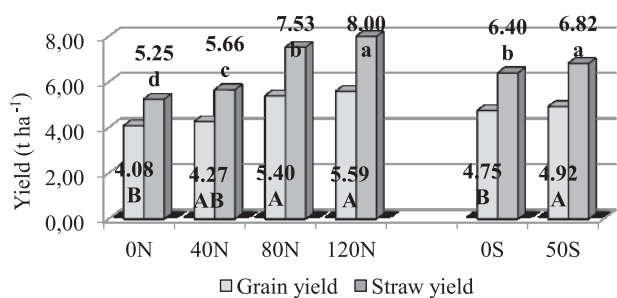


Fig. 1. Effect of nitrogen and sulphur fertilization as well as study year on grain and straw yields of spring wheat. Values with different letters in the column differ significantly ( $P < 0.05$ ).

S fertilization increased grain yield by 3.58%. The straw yield increased proportionally as the N application rate increased (Fig. 1). According to Potarzycki [11], the use of fertilizers containing sulfur affects the greater the accumulation of N in the grain. In a study by Podleśna [12], S fertilization of winter wheat at a rate of 60 kg S ha<sup>-1</sup> led to an increase in grain yield of 11%. In the presented research the content and uptake of nitrogen by the spring wheat grain significantly increased in direct proportion to the increase in the N application rate and was the highest following the application of 120 kg N ha<sup>-1</sup> (N content of 28.59 g kg<sup>-1</sup> DM and N uptake of 141.5 kg ha<sup>-1</sup>). The content of N in the spring wheat straw significantly increased to the rate of 80 kg N ha<sup>-1</sup>. However, the highest content and uptake of N by straw was found after the application of 120 kg N ha<sup>-1</sup> (N content of 6.50 g kg<sup>-1</sup> DM and N uptake

of 46.1 kg ha<sup>-1</sup>). Also, Knapowski et al. [13] significantly had the highest N content in the triticale grain after the application of the highest N dose, i.e., 120 kg ha<sup>-1</sup>, and this was higher compared to the object fertilized with 80 kg N ha<sup>-1</sup> by 1.1 g N kg<sup>-1</sup> DM. The nitrogen application at the rates of 80 and 120 kg N ha<sup>-1</sup> decreased HI<sub>N</sub> significantly in relation to control, and to the lowest rate (i.e., 40 kg ha<sup>-1</sup>). Similarly, Flood and Martin [14] indicate a positive correlation between wheat grain yield and N harvest index and a negative correlation between the content of N in the grain and HI<sub>N</sub>. According to Bänziger [15], the content of total N in the grain correlates positively with the N harvest index. The response of wheat to N is in accordance with several such reports available in literature [5]. The addition of S to N application significantly increased the yield of grain and straw, the content and uptake of N, and the decrease of HI<sub>N</sub> (Table 1). Also in studies of Podleśna et al. [16], S fertilization increased the N index harvest compared to objects without S. Similarly, a response to S fertilization has been reported by a number of researchers [17-19]. Przygocka-Cyna and Grzebisz [20-21] indicate that S fertilization can lead to a reduction in N content in the grain as a result of the grain yield increase, and described the phenomenon as the effect of dilution. Meanwhile, Barczak [22] showed that S fertilization resulted in an increase in the content of total N in spring barley. Also in studies of Martin [23] and Reussi et al. [24], the increasing level of sulfur increased noticeably the N content in grains of wheat.

The content and uptake of S by the spring wheat grain significantly increased together with the N application rate increase and were highest following the application

Table 1. Content and uptake of N by spring wheat (mean of three years).

S and N treatment		N content (g kg <sup>-1</sup> DM)		N uptake (g ha <sup>-1</sup> )			N harvest index (%)
		Grain	Straw	Grain	Straw	Total	
0S (N × S)	0	25.40 a	5.51 a	90.3 a	24.8 a	115.1 a	78.50 a
	40	26.88 a	5.89 a	98.4 a	28.5 a	126.9 a	77.53 a
	80	27.69 a	6.58 a	131.2 a	42.0 a	173.2 a	75.80 a
	120	28.40 a	6.51 a	137.3 a	45.6 a	183.0 a	75.07 a
50S (N × S)	0	25.61 a	5.74 a	93.1 a	27.9 a	120.9 a	77.03 a
	40	27.58 a	6.02 a	106.6 a	31.1 a	137.8 a	74.23 a
	80	27.81 a	6.65 a	133.6 a	46.3 a	179.9 a	74.23 a
	120	28.78 a	6.48 a	145.6 a	46.7 a	192.2 a	75.73 a
0S	Mean	37.09 B	6.13 A	114.3 B	35.2 B	149.5 B	76.73 A
50S	(S)	37.44 A	6.23 A	119.7 A	38.0 A	157.7 A	76.10 B
Mean (N)	0N	25.50 C	5.63 B	91.7 D	26.3 C	118.0 D	77.77 A
	40N	27.23 B	5.96 AB	102.5 C	29.8 B	132.3 C	77.47 A
	80N	27.75 B	6.62 A	132.4 B	44.1 A	176.6 B	75.02 B
	120N	28.59 A	6.50 A	141.5 A	46.1 A	187.6 A	75.40 B

Values with different letters in the column differ significantly ( $P < 0.05$ ).

Table 2. Content and uptake of S by spring wheat (mean of three years)

S and N treatment		S content (g kg <sup>-1</sup> DM)		S uptake (g ha <sup>-1</sup> )			S harvest index (%)
		Grain	Straw	Grain	Straw	Total	
0S (N × S)	0	1.24 a	1.08 a	4.44 a	4.85 a	9.28 a	49.27 a
	40	1.24 a	1.10 a	4.56 a	5.36 a	9.91 a	45.93 a
	80	1.33 a	1.25 a	5.99 a	7.97 a	14.29 a	44.23 a
	120	1.37 a	1.12 a	6.64 a	7.86 a	15.40 a	45.80 a
50S (N × S)	0	1.25 a	1.10 a	4.60 a	5.33 a	9.92 a	46.23 a
	40	1.28 a	1.12 a	4.96 a	5.81 a	10.76 a	46.00 a
	80	1.34 a	1.18 a	6.44 a	8.20 a	14.64 a	44.00 a
	120	1.40 a	1.18 a	7.09 a	8.48 a	15.57 a	45.47 a
0S 50S	Mean (S)	1.30 B 1.32 A	1.14 A 1.14 A	5.41 B 5.77 A	6.51 A 6.96 A	12.00 B 12.73 A	46.31 A 45.43 B
Mean (N)	0N	1.25 C	1.09 BC	4.52 BC	5.09 B	9.60 B	47.75 A
	40N	1.26 C	1.11 BC	4.76 C	5.58 B	10.34 B	45.97 B
	80N	1.34 B	1.21 A	6.21 B	8.09 A	14.47 A	44.12 BC
	120N	1.39 A	1.15 B	6.87 A	8.17 A	15.04 A	45.63 B

Values with different letters in the column differ significantly ( $P < 0.05$ ).

of 120 kg N ha<sup>-1</sup> (S content – 1.39 g kg<sup>-1</sup> DM and S uptake – 6.87 kg ha<sup>-1</sup>). The content of S in the straw of spring wheat significantly increased to the rate of 80 kg N ha<sup>-1</sup> (1.21 g kg<sup>-1</sup> DM). Although the uptake of S by straw also significantly increased to the rate of 80 kg N ha<sup>-1</sup>, the highest uptake of S by straw was found after the application of 120 kg N ha<sup>-1</sup> (S – 8.17 kg ha<sup>-1</sup>). Howarth et al. [25] concludes that N deficiency caused a slower accumulation of N and S in grain, which resulted in lower final content of these elements. A study by Potarzycki [7] showed that spring barley well nourished by S is characterized by a lower N content in the straw. On the other hand, Gondek and Gondek [26] showed that spring wheat fertilization with S resulted in a significant increase in N content in the straw compared with control. Howarth et al. [25] concludes that S fertilization increased uptake of S by grain of 29.8%. In studies of Monaghan et al. [27], wheat grain accumulated to 50% of the total amount of S taken by biomass plant. According to the Kovar and Grant [28], S content of grain is generally higher than in vegetative tissue of plants and also the contents of the elements in the plants vary depending on its development phase [29]. The N application at each rate and the addition of S to N decreased significantly the S harvest index (HI<sub>S</sub>). Although the addition of S to N application significantly increased the S content and its uptake by grain and total S uptake (grain + straw), there is no impact on these parameters of straw (Table 2). A study led by Fotyma [30] on fertilization of spring wheat with S showed that the application of 60 kg S ha<sup>-1</sup> increased grain yield and N uptake, but did not affect the accumulation of S in the grain. Fotyma [30] claims that S indirectly increases crop yield by influencing N transformation in the plant. Podleśna [12] emphasizes

that the application of S in fertilization of spring wheat and rapeseed had a beneficial effect on grain and seed yield by contributing to the appropriate content of S and N, the correct development of aerial parts, and the formation of the root system. Moreover, Podleśna [12] showed that N uptake was dependent on efficient S fertilization. Reussi et al. [24] say that S and N interact on their concentration in plants and the total accumulation in yields, as the S content in the grain of wheat depends not only on its dose, but also on the availability of N. The interaction of these elements at the level of the many metabolic processes is reflected in the growth and development of crops, which ultimately affects the level and quality of their yield.

In another study Fotyma [31] stated that the effectiveness of nitrogen can be evaluated using such indicators as agricultural efficiency and physiological efficiency. These indicators allow us to determine the ability of plants to process downloaded N on yield. According to Rutkowska [32], both of these indicators reach the largest values in a range of small doses of fertilizer and decrease with the level of fertilization. It was similar in the presented research. The application of 40 kg N ha<sup>-1</sup>, in comparison with the control (without N), caused an increase in the grain yield of the spring wheat of 2.9 kg per kg N applied in the fertilizer. Increasing the N application rate to 80 kg ha<sup>-1</sup> caused an increase in the grain to reach 16.6 kg per kg N, while the rate of 120 kg N ha<sup>-1</sup> reduced the increase to 12.0 kg per kg of N (Table 3, Fig. 2). The greatest increase in grain per kg applied N was observed where the application rate was increased from 40 to 80 kg N ha<sup>-1</sup>, and it amounted 30.4 kg grain per kg N (Table 3). The addition of S to the lowest N application rate, 40 kg N ha<sup>-1</sup>, caused an increase in grain of 8.8 kg

Table 3. The indicators of N-S fertilization efficiency (mean three years)

Fertilizing combinations: nitrogen and sulphur		Efficiency of N fertilization		Efficiency of S fertilization		Utilization (%)		Final efficiency index***	
		*AE <sub>N</sub>	** PE <sub>N</sub>	*AE <sub>S</sub>	** PE <sub>S</sub>	U <sub>N</sub>	U <sub>S</sub>	EFI <sub>N</sub>	EFI <sub>S</sub>
N	0-40	2.9	14.3		972	20.2		0.7	
	0-80	16.6	32.5		707	51.2		3.9	
	0-120	12.0	30.6		652	39.2		4.0	
	40-80	30.4	37.0		689	82.2		7.1	
	40-120	16.5	34.0		634	48.7		5.6	
	80-120	2.7	17.1		333	39.2		4.0	
N × S	0-0+S			2.1	645		0.3		0.3
	0-40+S	8.8	21.6	7.0	676	40.8	1.0	4.9	2.2
	0-80+S	17.5	32.4	28.0	700	54.1	4.0	5.8	5.4
	0-120+S	14.0	30.0	33.7	635	46.0	5.3	4.5	6.2
	40-80+S	32.1	36.0	25.7	683	88.0	3.8	11.0	5.1
	40-120+S	19.6	33.0	31.4	619	59.0	5.1	6.4	5.9
	80-120+S	8.9	24.2	7.1	459	35.8	1.5	5.8	2.7
S	40+S-80+S	26.2	38.9		709	67.4		9.6	
	40+S-120+S	16.7	34.3		624	48.7		3.9	
	80+S-120+S	7.2	23.4		435	30.0		5.4	

\*Agronomic efficiency (AE) = 1 kg of grain/1 kg of a component in fertilizer;

\*\*Physiological efficiency (PE) = 1 kg of grain/1 kg of accumulated component;

\*\*\*Final efficiency index (EFI) = grain in PLN/ fertilizer in PLN (print prices IERGiŻ, July, 2012r.: grains of spring wheat:

1 Ton – 900 PLN, ammonium nitrate: 1 Ton – 1,390 PLN, kieserite: 1 Ton – 1,340 PLN, epsomite: 1 Ton – 1,200 PLN)

per kg N, which was a threefold increase in agronomic efficiency of N (AE<sub>N</sub>) in comparison with the variant without S. Among the combinations tested, the greatest AE<sub>N</sub> was noted in the case of 40 N – 80 N + 50 S, i.e., the increase in N fertilization to 80 kg ha<sup>-1</sup> with the addition of S increased the grain in the amount of 32.1 kg per kg N with S. This is also confirmed by the combination 40 N + 50 S – 80 N + 50 S, where an increase in grain of 26.2 kg per kg of applied nitrogen with S addition was obtained. The application of S in the control (without N) caused an increase in spring wheat grain as 2.1 kg per kg applied S fertilizer. The addition of N caused a directly proportional increase in grain as the application rate increased; it was highest following the application of 120 kg N ha<sup>-1</sup>: 33.7 kg per kg of S applied in the fertilizer. Potarzycki [11] claimed that S fertilization increased agricultural efficiency (agronomic) of N fertilizer.

Physiological efficiency (PE) showed a similar pattern to that of agronomic efficiency (AE). In the case of N, the increase in spring wheat grain per kg of accumulated N was at the application rate of 40 and 80 kg N ha<sup>-1</sup>, in comparison to the control, while the application of N at a rate of 120 kg ha<sup>-1</sup> reduced the increase of accumulated N (Table 3, Fig. 2). The addition of S to the lowest N application rate, 40 kg ha<sup>-1</sup>, caused a grain increase of 21.6 kg per kg of accumulated N, which was a 1.5-

fold increase in the physiological efficiency of N (PE<sub>N</sub>) in comparison to the variant without S. This means that S increased the physiological efficiency of N uptake by the spring wheat grain one and a half times. The physiological efficiency of the effect of S (PE<sub>S</sub>) alone, without taking N into account (control), was very high, as 1 kg of accumulated S caused an increase in spring wheat grain by 645.4 kg. The application of N and S together caused the physiological efficiency of S (PE<sub>S</sub>) to increase by 4.8% and 8.5% for the application of 40 and 80 kg N ha<sup>-1</sup>, respectively, while the addition of S to 120 kg N ha<sup>-1</sup> caused a decrease in the physiological efficiency of S (PE<sub>S</sub>) in comparison to all other combinations tested. The physiological efficiency of S (PE<sub>S</sub>) calculated in the control variant, in conditions of natural soil without N and S fertilizer, was 972.2 kg of grain per kg of accumulated S, and then each addition of N fertilizer caused a decrease in the effect of S on grain yield (Table 3, Fig. 2). In the studies of Fotyma [31] these indicators of N had higher values after the application of S fertilizer.

The highest utilization of N (U<sub>N</sub>) by spring wheat was obtained following the application of 80 kg N ha<sup>-1</sup> (51.2%), and the most beneficial option was the increase from 40 to 80 kg ha<sup>-1</sup> (82.2%). The highest application rate of 120 kg N ha<sup>-1</sup> caused a decrease in utilization of N (U<sub>N</sub>). The low utilization of N (U<sub>N</sub>) following the application



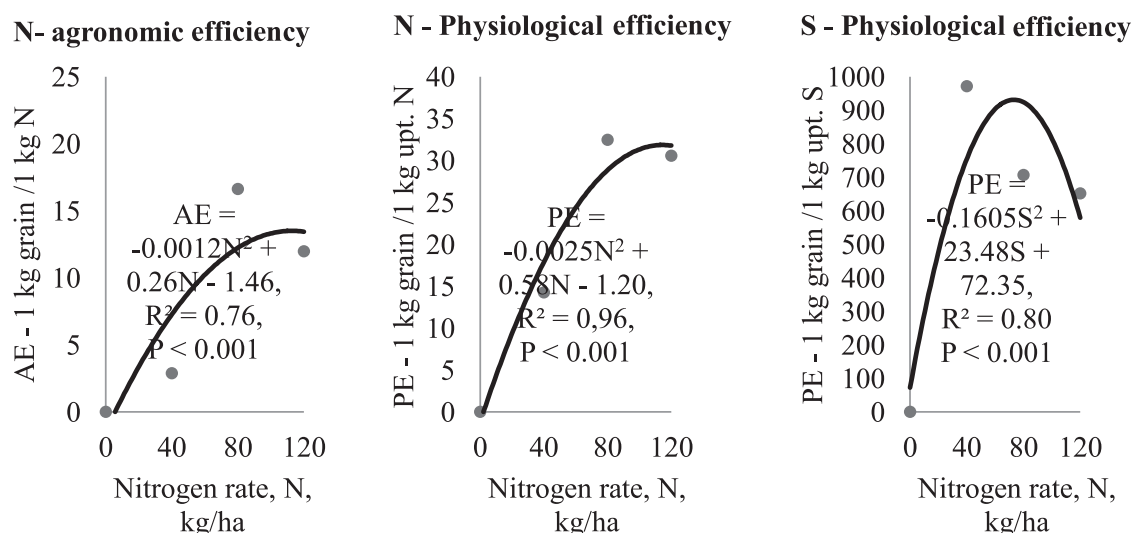


Fig. 2. The influence of N fertilization on agronomic (AE) and physiological efficiency (PE) of nitrogen and sulphur in spring wheat production ( $n = 4$ ).

of 40 kg ha<sup>-1</sup> (20.2%) may indicate that the N was used to improve the state of the plants and to build vegetative parts, but it was too low a dose to achieve a high yield (Table 3). The distribution of the final efficiency index of N (EFI<sub>N</sub>) was similar, as it was closely correlated with the utilization of N (U<sub>N</sub>) by the spring wheat grain. Zhang et al. [33] have reported that only 30-35% of the N from the fertilizers is used by plants. According to Hirel et al. [34], in an intensive system of agricultural production from 50 to 75% of the N from the fertilizer is not used for field crops. According to these authors [33-34], the unused N is the main source of nitrate pollution of the groundwater. However, the balanced fertilization is a factor that causes the increase in the level of N utilization by crops.

The utilization of S (U<sub>S</sub>) in the control, without N fertilizer, was 0.3% and increased to 5.3%, in direct proportion following the application of 120 kg N ha<sup>-1</sup>. This indicates that N increases S uptake and vice versa, but only the proper N:S ratio supplied to plants. In the case of the highest application rate of 120 kg N ha<sup>-1</sup> supplemented with S, the utilization of S (U<sub>S</sub>) was only 1.6% in comparison to the 80 kg N ha<sup>-1</sup> variant. This case as well as the final efficiency index of S (EFI<sub>S</sub>) were closely correlated with the utilization of S (U<sub>S</sub>) by the spring wheat grain. Potarzycki [35] reports that the utilization of N by spring barley and the agronomic efficiency of N fertilization depended on S fertilization. Also, Salvagiotti et al. [36] are of the opinion that S fertilization increases the use of N from fertilizers. Szczepaniak [7] concluded that magnesium and phosphorus in maize tissues are at physiological maturity. Utilization of S by plants cultivated in the control (N0) was 0.32% and increased to 5.31% after the application of 120 kg N ha<sup>-1</sup>. This indicates that N also assists S uptake and vice versa, but only to a certain point, as in the case of the highest rate of 120 kg N ha<sup>-1</sup> supplemented with S, utilization of S was only 1.55% in comparison with 80 kg N ha<sup>-1</sup>. Taking into account all the fertilizer combinations

with N and S, we can conclude that the highest utilization of N (U<sub>N</sub>) and the best final efficiency index of N and S (EFI) resulted from the combined application of 80 kg N ha<sup>-1</sup> and 50 kg S ha<sup>-1</sup>. This combination should be recommended in practice for N and S fertilization of spring wheat. This is because increasing the N application rate to 120 kg ha<sup>-1</sup> causes a decrease in utilization of N (U<sub>N</sub>), and adding S causes a decrease in utilization of S (U<sub>S</sub>) by the grain. This phenomenon should be explained by the law of decreasing increments (Mitscherlich law) [9]. Wojciechowski [37] demonstrated that after the increase in the application rate from 40 to 80 kg ha<sup>-1</sup>, N utilization was 38.6% higher than for the fertilization range of 80-120 kg, and 72.7% higher than for 0-40 kg ha<sup>-1</sup>. In the study of Shivay et al. [1], 5% of S-coated urea (SCU) supplied 50% of the S needs of the wheat crop and increased recovery efficiency by 60.3% over N application as uncoated prilled urea (PU). According to Monaghan et al. [27], 50% of S accumulated in the kernels is taken up by wheat in the period after flowering. Thus the selection of fertilizer for spring wheat and other cereals should take into account the demand of this species for S during the entire vegetative season, i.e., both in the stem elongation stage [3] and near the end of vegetation [9, 38-40].

## Conclusions

Polish agriculture must use the rules of an integrated production system. Then it should be taken into account that the application of mineral nutrients should be lower than the plant uptake level. In this situation spring wheat fertilization with 80 kg N ha<sup>-1</sup> and 50 kg S ha<sup>-1</sup> should be recommended in practice as the present study indicated that it guarantees the highest seed yield and the highest utilization of N from fertilizers.

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