

Article

Efficiency of Nitrogen Fertilization of Winter Wheat Depending on Sulfur Fertilization

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Abstract: Optimization of fertilization enables to obtain a yield of high quality and quantity, brings economic profits, and reduces environmental threats. The aim of the three-year field experiment was to determine the efficiency of fertilization with a new fertilizer available on the Polish market and containing nitrogen (N) and sulfur (S) in proportions designed for cereals cultivation (30% N and 6% S as ammonium nitrate and ammonium sulfate). Other treatments included no fertilization; fertilization with ammonium nitrate (34% N); fertilization with standard nitrogen and sulfur fertilizer with N supplementation with ammonium nitrate. Nitrogen doses were 150, 200, and 250 kg N ha⁻¹. Sulfur was applied in doses of 30, 40, and 50 kg S ha⁻¹. A beneficial effect of using fertilizer containing N and S in proportions designed for cereals cultivation was observed. The highest mean optimal nitrogen dose and maximum winter wheat yield were recorded for the new fertilizer (217 kg N ha⁻¹ and 8251 kg ha⁻¹, respectively). Sulfur supplementation with the new fertilizer significantly increased apparent nitrogen recovery (mean values 48.9%, 44.6%, and 40.6% for doses 150, 200, and 250 kg N ha⁻¹, respectively), agronomic efficiency (11.1 and 8.6 kg kg⁻¹ N for doses 200 and 250 kg N ha⁻¹, respectively), and physiological efficiency (24.7 kg kg⁻¹ N for dose 200 kg N ha⁻¹).

Keywords: ammonium nitrate; ammonium sulfate; fertilization efficiency; cereals

1. Introduction

Wheat (*Triticum L*) was one of the first domesticated plants and has been the staple food for major civilizations in Europe, West Asia, and North Africa over many thousands of years. Domestication of wheat was probably the most important step in humanity's transition from hunter-gatherer and nomadic shepherd to settled farmer [1].

Nowadays, wheat is an economically important crop cultivated worldwide [2–4]. It is one of three cereals (next to rice and corn) which are the most important food sources for people, and whose total global consumption accounts for over 90% of total cereal consumption [5–8]. In 2018, wheat was grown on 214 million hectares of land worldwide. The production amounted to 734 million tons, with an average yield of about 3.4 tons per hectare [9]. The forecasts indicate that in 2020, 761.5 million tons of wheat will be produced worldwide [10]. In 2018, Asia generated 44.7% of worldwide wheat production, Europe—33.0%, Americas—15.4%. Twenty-eight European Union (EU) Member States produced 138 million tons of this cereal on a 25.5 million ha area, with an average yield of about 5.5 tons per hectare. The main wheat producers in the EU include France, Germany, the United Kingdom, Romania, and Poland. In 2018, wheat was grown on 2.4 million ha in Poland, providing an output of 9.8 million tons (average yield was 4.1 tons per hectare) [9].

Wheat popularity and success can mainly be attributed to the fact that it is unrivaled in its range of cultivation. It can be grown in many areas with different weather, elevation, or soil properties. Not only conventional mineral fertilizers, but also organic materials can be used for fertilization [11]. In addition, wheat is the most versatile grain among the cereals used for food, supplying more proteins and calories to the global population than any other agricultural food [4,12–14].

Wheat yield efficiency is a complex of many natural and agrotechnical factors and their mutual connections (crop genotype, soil type, crop management, atmospheric dioxide concentration, and weather conditions) [1,7]. Abiotic stresses such as extreme temperatures and water shortage due to changing climate may affect the productivity of cereals worldwide [3]. Wheat grows preferentially in cooler temperatures (the optimum temperature for growth: 15–25 °C) [15]. Temperature changes during vegetation can potentially decrease wheat productivity in certain regions [16–18]. Among the major staple crops, wheat is the most drought resistant and most water-use efficient [2]. However, drought may also reduce wheat harvest [10].

Worldwide production systems differ significantly not only in climatic conditions, but also in soil fertility. In all agricultural systems there is a need for giving plants access to adequate elements, introduced in appropriate doses—in general, nutrients are supplied as fertilizers in areas of advanced production [19]. Mineral fertilizers play a significant role in replenishing shortages of nutrients for plants, improving crop productivity and preventing losses of yield quantity and quality [20]. Total global demand for fertilizers (as N, P₂O₅, K₂O), exceeded 185 million tons in 2016, of which the demand for N fertilizers was over 105 million tons [21]. The total global demand for N will reach 112 million tons in 2022. In terms of world regions, the highest demand for N fertilizers in 2016 was recorded in Asia (59.2 million tons). Americas and Europe have considerably lower demand for N fertilizers. However, on a global scale, they are right behind Asia, i.e., the demand in 2016 was 23.4 and 16.5 million tons, respectively. In 2022 the demand for N fertilizers in Asia, Americas, and Europe will reach 62.0, 25.0, and 17.6 million tons, respectively [21]. At the same time, attention is drawn to the need to reduce fertilizer use because of environmental reasons [22].

The unsuitable management of nitrogen fertilization may not only reduce wheat yield [23–26], but also lead to losses of this nutrient caused by leaching, runoff, volatilization, or denitrification. Therefore, optimizing the use of N fertilizers is important as it ensures economic sustainability of cropping systems and suitable plant production, and at the same time reduces environmental threats caused by the introduced nitrogen [16,23,27–29]. This research area has become a major focus of recent agricultural research, mainly due to the fact that N fertilizer has become the largest input cost, and because of the demand and production costs its price continues to increase [30]. Proper plant supply with other nutrients is important for effective nitrogen fertilization [31]. The effect of nitrogen (N) and sulfur (S) fertilizers on crop production has been widely investigated, and these nutrients are normally considered as key factors in cereal production. This is because they affect rapid plant growth and improve the quality and quantity of grain yield [25,29,31,32]. Grain protein content is a major determinant of wheat grain quality, which is the subsequent effect of N and S fertilization. These macronutrients build blocks of proteins. Nitrogen fertilization increases grain protein content, while sulfur fertilization affects grain protein composition [33–35]. Due to insufficient S supply, wheat is not capable of reaching its full yield potential [36], and the use of N for protein synthesis may be reduced [30].

Due to the fact that the human population is growing, and, in consequence, food consumption is increasing, crop production must be intensified by roughly 70% by 2050 and doubled or tripled by 2100 to provide food security for people [14,37,38]. Exploring the possibilities of increasing plant production, and efficient use of N fertilizers without posing environmental threats is an important research area [38,39].

The aim of this study was to determine the efficiency of winter wheat fertilization with ammonium nitrate enriched with ammonium sulfate. The effect of a new fertilizer (containing 30% N and 6% S) available on the Polish market was analyzed. Based on the results of a three-year field experiment,

the following parameters were calculated: optimal nitrogen dose and maximum yield of winter grain for that dose, marginal efficiency of fertilization, agronomic efficiency, nitrogen uptake, apparent nitrogen recovery, physiological efficiency.

2. Materials and Methods

2.1. Field Experiment

The field experiment was set up in 2014 at the experimental station of the University of Agriculture, located in Krakow-Mydlniki in Poland (N 50.091568, E 19.857655). The experiment was established on Stagnic Luvisol. The soil has heavy category (36% fraction < 0.02 mm), acid reaction (pH_{KCl} 4.88), low content of total sulfur (0.16 g kg⁻¹ DM) and sulfate sulfur (8.92 mg kg⁻¹ DM), and medium content of available phosphorus (63.4 mg kg⁻¹ DM) and potassium (238 mg kg⁻¹ DM).

The experiment comprised 10 treatments, each conducted in four replications (the area of a single experimental plot was 28 m² = 7 × 4 m):

- I: no fertilization (control);
- II, III, and IV: 150 kg N, 200 kg N, and 250 kg N ha⁻¹, respectively, with no S fertilization—as ammonium nitrate (34% N);
- V, VI, and VII: 150 kg N and 30 kg S ha⁻¹, 200 kg N and 40 kg S ha⁻¹, 250 kg N and 50 kg S ha⁻¹, respectively—S was introduced with fertilizer A (a mixture of ammonium nitrate and ammonium sulfate, 26% N and 13% S) conventionally available on the Polish market; N dose was supplemented with ammonium nitrate;
- VIII, IX, and X: 150 kg N and 30 kg S ha⁻¹, 200 kg N and 40 kg S ha⁻¹, 250 kg N and 50 kg S ha⁻¹, respectively—S and N were introduced with fertilizer B (a mixture of ammonium nitrate and ammonium sulfate, 30% N and 6% S) which was a new fertilizer available on the Polish market and containing N and S in proportions designed for cereals cultivation.

The experiment was conducted for three growing seasons, and winter wheat cv. Natula (a quality cultivar with very high technological parameters of the grain) was the test plant in all seasons. Sugar beet was the forecrop for winter wheat cultivation. Phosphorus and potassium were applied before sowing of wheat (30.50 kg P ha⁻¹ as 40% superphosphate and 83 kg K ha⁻¹ as 60% potassium salt each year). Nitrogen was applied at the beginning of spring vegetation (dose of 50%), at the beginning of stem elongation phase (30%) and prior to heading (20%). Wheat was harvested at full grain maturity and the amount of grain yield was determined.

Humidity and thermal conditions during the experiment are shown in Figure 1. The growing seasons varied in weather conditions. The sum of precipitation for the first growing season (2014/2015) was 593 mm, for the second one (2015/2016) it was 696 mm, and for the third season (2016/2017) it was 826 mm. The precipitation distribution in particular months was not optimal. High precipitation was recorded especially in July of the second growing season (180 mm, which was 26% of the total precipitation in the growing season) and in January of the third season (148 mm, which was 18% of the total precipitation). The mean air temperature in the first and second season was 9.6 °C, and in the third season it was 8.5 °C. Despite similar mean air temperature, thermal conditions varied between seasons. During the third season, temperature in winter months was the lowest. From February to June, the highest mean temperatures were determined in the second growing season. At the same time, it was the season with very low precipitation from March to June (water deficiency was supplemented only in July), which created unfavorable conditions for wheat growth.

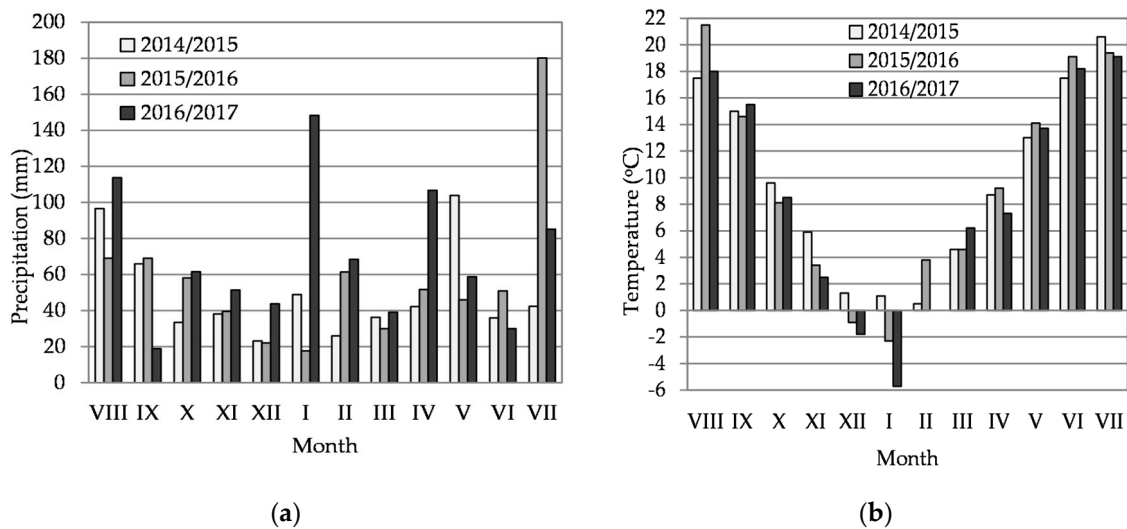


Figure 1. Weather conditions for particular months of three seasons of winter wheat growth: (a) total precipitation; (b) mean air temperature.

2.2. Calculations

The curves of winter wheat response to N fertilization were determined based on the second-degree polynomial equation (the x -axis shows N doses, and the y -axis shows the yield of winter wheat grain) [40]:

$$y = a + bx + cx^2 \quad (1)$$

The highest point on the graph of quadratic function shows the optimal N dose and maximum yield of winter wheat grain for that dose. The optimal N dose (D_{opt}) was calculated as:

$$D_{opt} = -b/2c \quad (2)$$

and maximum yield (Y_{max}) as:

$$Y_{max} = (a - b^2/4c) \quad (3)$$

Marginal efficiency (E_m), determining the increase in plant yield per 1 kg of nutrient (kg kg^{-1} N) at any given dose within a given range, was established as the first derivative of the polynomial function:

$$E_m = b + 2cx \quad (4)$$

Once the D_{opt} is exceeded, the E_m parameter assumes negative values.

Agronomic efficiency (E_a) of nitrogen fertilization of winter wheat was calculated according to the equation ([41], after Dobermann 2007):

$$E_a = \frac{Y - Y_0}{D} \quad (5)$$

where:

E_a —agronomic efficiency of nitrogen fertilization (kg kg^{-1} N),

Y —yield of fertilized plants (kg ha^{-1}),

Y_0 —yield of control plants (unfertilized) (kg ha^{-1}),

D —nitrogen dose (kg N ha^{-1}).

Agronomic efficiency is a parameter that determines the increase in plant yield in a given range of nutrient doses.

Nitrogen uptake was calculated by multiplying the amount of yield and N content in that yield (arithmetic mean N content in the yield for a particular treatment and for a particular year of

experiment were used; N content was determined with a vario MAX cube CNS elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany)). Apparent nitrogen recovery (R) was calculated as:

$$R = \frac{U - U_0}{D} \cdot 100\% \quad (6)$$

and physiological efficiency (E_p) was calculated according to the equation ([41], after Dobermann 2007):

$$E_p = \frac{Y - Y_0}{U - U_0} \quad (7)$$

where:

R —apparent nitrogen recovery (%),

U — nitrogen uptake by fertilized plants (kg N ha^{-1}),

U_0 — nitrogen uptake by control plants (unfertilized) (kg N ha^{-1}),

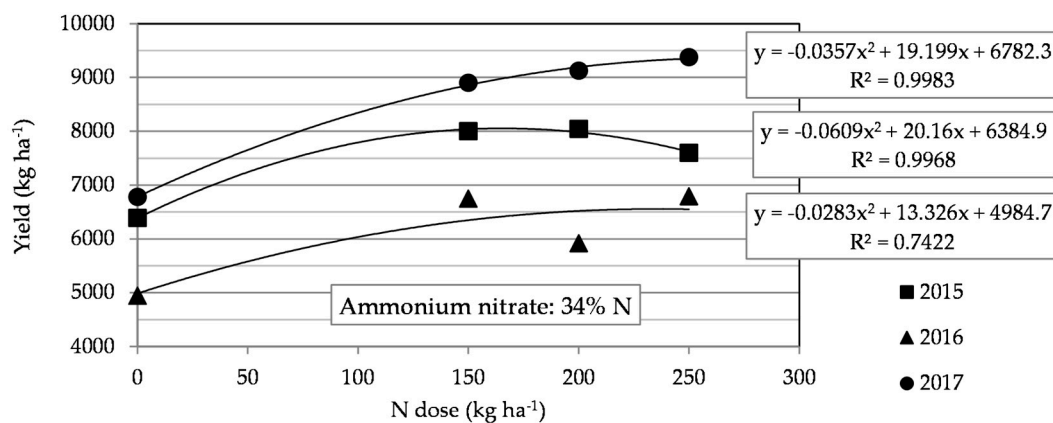
E_p —physiological efficiency of fertilization ($\text{kg kg}^{-1} \text{N}$).

2.3. Statistical Analysis

The obtained results of agronomic efficiency, nitrogen uptake, nitrogen recovery, and physiological efficiency were statistically analyzed. A two-way analysis of variance (factor 1: treatment, factor 2: year) was performed using PQStat, ver 1.6 (PQStat Software, Poznań, Poland) statistical package. The least significant differences (LSD) were calculated by the Fisher's test ($\alpha = 0.05$).

3. Results and Discussion

The amount of winter wheat yield is shown as a function (a second-degree polynomial equation $y = a + bx + cx^2$) of N fertilization. Vertices of the curves mark the optimal N doses and the maximum yields of winter wheat grain for those doses (higher N doses did not increase the yield). Figure 2 shows curves of winter wheat response to fertilization with individual fertilizers and in individual years, whereas Figure 3 shows mean curves for three years of research.



(a)

Figure 2. Cont.

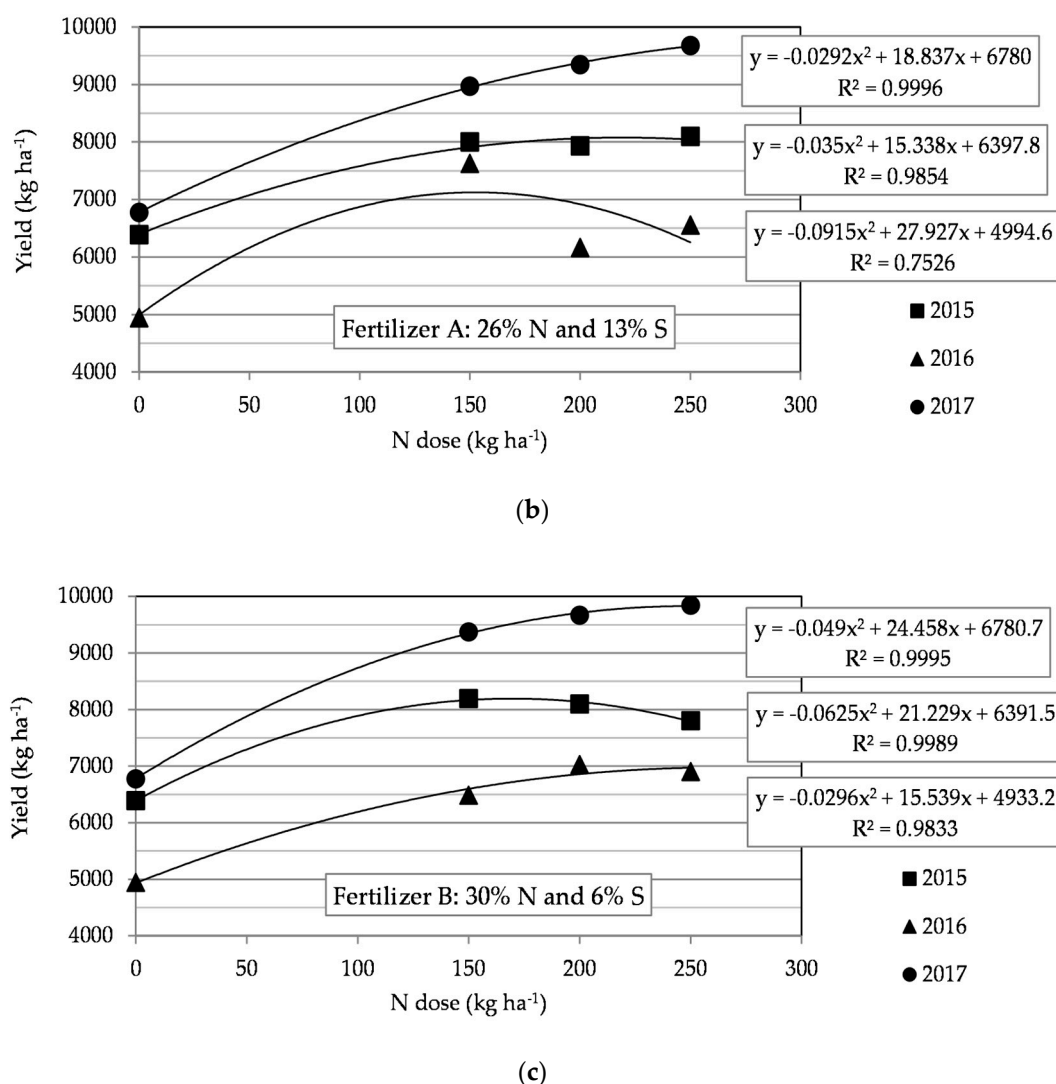


Figure 2. Winter wheat yield as a function of nitrogen fertilization in individual years: (a) curves of winter wheat response to fertilization with ammonium nitrate; (b) curves of winter wheat response to fertilization with fertilizer A: 26% N and 13% S; (c) curves of winter wheat response to fertilization with fertilizer B: 30% N and 6% S.

When analyzing mean values for three years of research, the highest D_{opt} and Y_{max} were recorded for the treatment with the use of fertilizer B (30% N and 6% S)—217 kg N ha⁻¹ and 8251 kg ha⁻¹, respectively (Table 1). The mean Y_{max} of winter wheat fertilized with ammonium nitrate (without S) was 2.7% lower than the yield obtained after fertilization with fertilizer A, and 4.2% lower than the yield obtained after fertilization with fertilizer B.

The exact values of the optimal N dose (D_{opt}) and maximum wheat grain yield (Y_{max}) for that dose are shown in Table 1—the values change depending on treatment and year of the experiment. However, regardless of the experimental treatment, notably the lowest yields (mean value 6770 kg ha⁻¹) were collected in the second year of research. This can be explained by unfavorable weather conditions, especially very low precipitation (Figure 1). In general, increased soil water content enhances crop yield response to N fertilization, in particular when high N rates are applied [42].

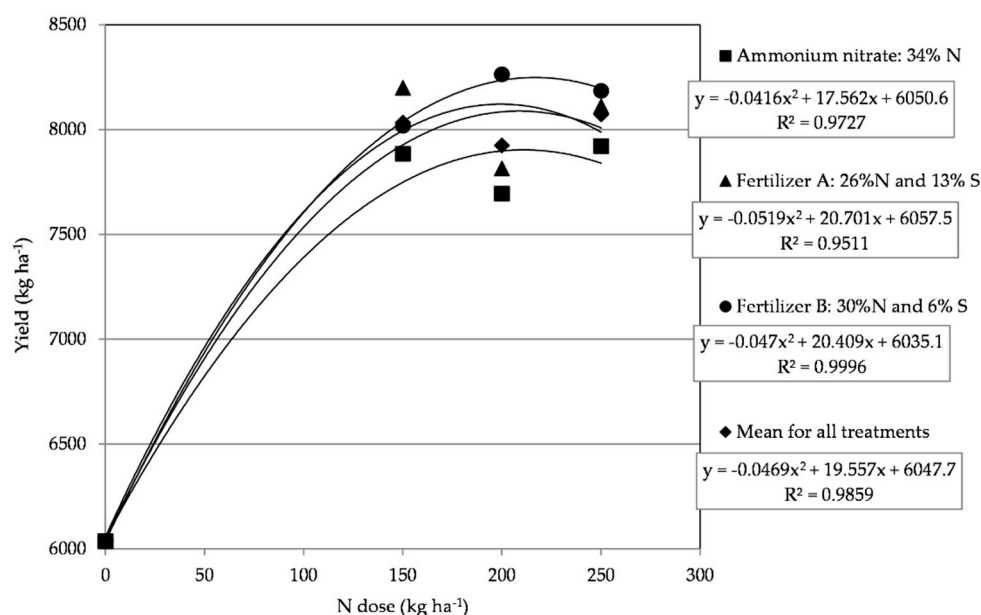


Figure 3. Winter wheat yield as a function of nitrogen fertilization (mean for three years of research).

Table 1. Optimal N dose and maximum yield of winter wheat grain for that dose.

Treatment	Optimal N Dose (kg N ha ⁻¹)				Maximum Yield (kg ha ⁻¹)			
	2015	2016	2017	Mean	2015	2016	2017	Mean
Ammonium nitrate: 34% N	166	235	269	211	8053	6553	9364	7904
Fertilizer A: 24% N and 13% S	219	153	323	199	8078	7126	9818	8122
Fertilizer B: 30% N and 6% S	170	262	250	217	8194	6973	9833	8251
Mean for all treatments	179	190	274	208	8084	6770	9636	8086

The optimal N rate varies depending on the cultivar, but also on the site and year of cultivation. This is due to the spatial variability of crop growing conditions and soil properties [43]. Zhang et al. [44] indicated that discrepancies in the optimal N dose and maximum yield may have resulted from environmental variability. Walsh et al. [45] did not find any significant differences in wheat grain yield under two levels of N fertilization: 90 and 135 kg N ha⁻¹. Haile et al. [46] reported that different rates of N fertilization significantly increased wheat grain yield, and its maximum was achieved by application of 120 kg N ha⁻¹ (however, optimal yield was not achieved as the response apparently did not plateau out). Litke et al. [47] observed a significant wheat grain yield increase up to the rate of 180 kg N ha⁻¹, and Duan et al. [48] up to the rate of 150 kg N ha⁻¹. According to Ali et al. [49], increasing N doses increase plant height as they stimulate the vegetative development, and thus grain yield is reduced. Aizpurua et al. [50], using the quadratic plateau response model, found that the optimal N dose was 182 kg N ha⁻¹. Zhang et al. [44], based on the linear plateau model, found that the optimal N dose (for field trials conducted at 120 sites) varied from 84 kg to 270 kg N ha⁻¹, with a mean value of 138 kg ha⁻¹, under which the maximum wheat yield varied from 5213 kg to 8785 kg ha⁻¹ with an average value of 6789 kg N ha⁻¹. Beneficial effect of S introduction under N fertilization on wheat grain yield was confirmed by Salvagiotti et al. [51], Klikocka et al. [52], and Rossini et al. [26] and explained by greater accumulation of nitrogen in the grain.

The effectiveness of nitrogen fertilization can be assessed not only by the quantity of the yield obtained, but also by other indicators, such as marginal efficiency, agronomic efficiency, physiological efficiency, and nitrogen recovery [53,54]. These parameters show the ability of plants to convert the uptaken N to yield; values of these parameters decrease as the fertilization level increases [52,55].

In general, lower crop nitrogen efficiency under its high input is a result of reusing nitrogen accumulated in tissues, in relation to lower N uptake [56].

The marginal efficiency (E_m) of nitrogen fertilization on wheat grain yield is presented in Figure 4. For the entire research period, E_m of fertilizer B was higher than that of ammonium nitrate or approximated it. Such a relationship for fertilizer A was observed in the first and third year of the research.

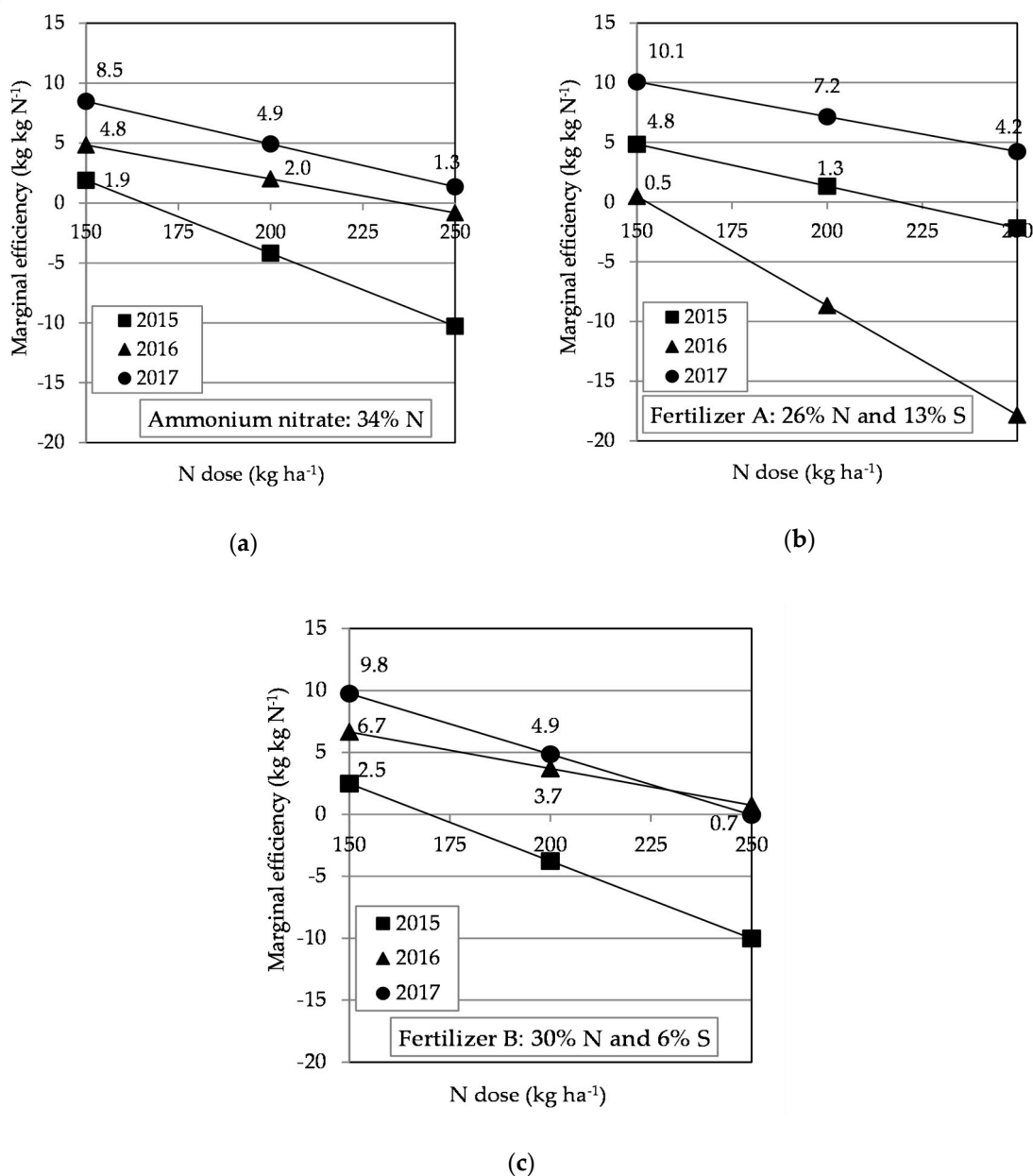


Figure 4. Marginal efficiency of N fertilization of winter wheat: (a) marginal efficiency of fertilization with ammonium nitrate; (b) marginal efficiency of fertilization with fertilizer A: 26% S and 13% N; (c) marginal efficiency of fertilization with fertilizer B: 30% N and 6% S.

The agronomic efficiency (E_a) of N varied from 4.8 kg kg^{-1} N, depending on N dose, the type of fertilizer, and the year of research (Table 2). E_a was visibly higher in the third year of the experiment than in the first and second year. When analyzing mean E_a values for three years of research, significantly higher values were obtained after fertilization with 150 kg N ha^{-1} (12.3–14.4 kg kg^{-1} N)

than after fertilization with 200 kg and 250 kg N ha⁻¹. Fertilization with sulfur, especially as fertilizer B, increased the E_a of N fertilization of winter wheat.

Table 2. Agronomic efficiency of N fertilization of winter wheat (kg kg⁻¹ N).

Treatment	Year			Mean	
	2015	2016	2017		
Ammonium nitrate: 34% N					
N dose (kg ha ⁻¹)	150	10.7	12	14.2	12.3
	200	8.3	4.9	11.7	8.3
	250	4.8	7.4	10.4	7.5
Fertilizer A: 26% N and 13% S					
N dose (kg ha ⁻¹)	150	10.7	17.9	14.6	14.4
	200	7.7	6.1	12.8	8.9
	250	6.8	6.4	11.6	8.3
Fertilizer B: 30% N and 6% S					
N dose (kg ha ⁻¹)	150	12	10.3	17.3	13.2
	200	8.5	10.4	14.4	11.1
	250	5.7	7.8	12.3	8.6
Mean	8.4	9.2	13.3	10.3	
LSD _{0.05} for:					
Treatment	1				
Year	0.6				
Treatment × year	1.7				

The efficiency of nitrogen application is a valuable indicator of rationality of N supply. For wheat cultivation, the E_a value usually ranges from about 10 kg to 30 kg kg⁻¹ N, and over 30 kg kg⁻¹ N can be encountered in well-organized growth systems or on poor soils where low level of nitrogen fertilization occurs. A lower E_a value suggests that changes in N management can increase plant productivity, and its value for wheat depends mainly on N fertilization and climatic conditions [57,58]. Our findings are consistent with the findings of Ayadi et al. [56] who showed that E_a increased to 13.97 kg kg⁻¹ N after fertilization with 150 kg N ha⁻¹ (further increasing the N dose decreased the E_a). Belete et al. [59] also noted a decreasing trend in nitrogen agronomic efficiency with increasing N fertilization—from 120 kg to 360 kg N ha⁻¹. In their study, Mandic et al. [57] obtained wheat yields that were generally not higher than 4.5 t ha⁻¹. For such relatively low yields, they obtained E_a values of 3.11 kg and 2.21 kg kg⁻¹ N for fertilization levels of 75 kg and 150 kg N ha⁻¹, respectively (no statistical differences between these values were determined). Klikocka et al. [52] checked results of fertilization with different doses of nitrogen and stated that E_a reached the highest value (32.1 kg kg⁻¹ N) after N fertilization at 80 kg N ha⁻¹ with the addition of sulfur at 50 kg S ha⁻¹. A significant effect of weather conditions on nitrogen agronomic efficiency was confirmed by Szmigiel et al. [60].

Nitrogen uptake by unfertilized wheat amounted to 91.0–114.5 kg N ha⁻¹ (Table 3). Fertilized plants took up from 148.5 kg to 240.3 kg N ha⁻¹, depending on N dose, the type of fertilizer and the year of research. The highest N uptake was recorded in the third year of research. When analyzing mean values for three years of research, significantly the highest values were obtained after fertilization with 250 kg N ha⁻¹ and 50 kg S ha⁻¹ (198.6–201.0 kg N ha⁻¹).

Table 3. Nitrogen uptake by winter wheat (kg N ha⁻¹).

Treatment	Year			Mean	
	2015	2016	2017		
Control (no fertilization)	93.3	91	114.5	99.6	
Ammonium nitrate: 34% N					
N dose (kg ha ⁻¹)	150	156.0	152.6	187.8	165.5
	200	159.2	148.5	209.0	172.2
	250	167.1	184.7	219.4	190.4
Fertilizer A: 26% N and 13% S					
N dose (kg ha ⁻¹)	150	151.2	186.1	193.8	177.0
	200	165.0	164.0	217.8	182.3
	250	175.7	182.9	237.2	198.6
Fertilizer B: 30% N and 6% S					
N dose (kg ha ⁻¹)	150	159.0	162.2	197.8	173.0
	200	171.7	182.0	212.7	188.8
	250	170.9	191.9	240.3	201.0
Mean	156.9	164.6	203.0	174.8	
LSD _{0.05} for:					
Treatment	4.2				
Year	2.3				
Treatment × year	7.3				

Klikocka et al. [52] observed that N uptake by wheat increased significantly after increasing the N dose, and amounted to 141.5 kg N ha⁻¹ under the application of 120 kg N ha⁻¹. Additionally, Wang et al. [42], for over 2 years of a field experiment, found that N uptake by wheat reached 39.5 kg, 58.5 kg, 75.2 kg and 103.8 kg N ha⁻¹ under N dose of 0 kg, 79 kg, 140 kg and 221 kg N ha⁻¹, respectively. As the authors noticed, a further increase in N dose to 300 kg N ha⁻¹ decreased N uptake by wheat to 92.3 kg N ha⁻¹. Salvagiotti et al. [51] found that N uptake by wheat increased with increasing N doses until the dose of about 80 kg N ha⁻¹. Moreover, they stated that S fertilization (at a dose of 30 kg S ha⁻¹) increased N uptake (the effect of sulfur intensified with increasing the N dose).

The apparent nitrogen recovery (R) depends on the congruence between plant demand for N and the quantity of this nutrient released from N fertilizer applied [59]. The R value in cereals, including wheat, ranges from 30% to 50%, and with lower N doses and best nutrient management it could reach 50–80% [61]. A low R value entails economic and ecological effects. The amount of nutrient that is not taken up by plants or soil microorganisms is lost in various ways [60,62]. In our research, the R value fluctuated between 28.8% and 63.4% (Table 4). The highest mean R value was recorded in the third year of research, then in the second year, and the lowest value was recorded in the first year of the experiment. When analyzing mean R values for three years of research, significantly the highest values were obtained after fertilization with 150 kg N ha⁻¹ (43.9–51.6%) than after fertilization with 200 kg and 250 kg N ha⁻¹. Sulfur fertilization (fertilizers A and B) significantly increased the R value for all N doses.

Szmigiel et al. [60] showed that applied nitrogen was most efficiently utilized by wheat when rates of 60 kg and 90 kg N ha⁻¹ were used (mean R of 42%), and at higher N doses that efficiency decreased, reaching the lowest value at 150 kg N ha⁻¹. These authors also pointed to a correlation between the nitrogen recovery value and weather conditions. They noticed that the higher the precipitation-evaporation quotient, the higher the nitrogen recovery. The decreasing R value as a result

of increasing N doses and relation of R with weather conditions has also been confirmed in other studies [42,63]. Furthermore, Wang et al. [63] indicated that suitable N fertilization for a high-yielding wheat ranged from 96 kg to 168 kg N ha⁻¹. Salvagiotti et al. [51] found that nitrogen recovery by wheat increased significantly under S fertilization at a dose of 30 kg S ha⁻¹, reaching almost 70% of the applied N.

Table 4. Apparent nitrogen recovery by winter wheat (%).

Treatment	Year			Mean	
	2015	2016	2017		
Ammonium nitrate: 34% N					
N dose (kg ha ⁻¹)	150	41.8	41	48.9	43.9
	200	33	28.8	47.2	36.3
	250	29.5	37.5	41.9	36.3
Fertilizer A: 26% N and 13% S					
N dose (kg ha ⁻¹)	150	38.6	63.4	52.8	51.6
	200	35.8	36.5	51.6	41.3
	250	33	36.8	49.1	39.6
Fertilizer B: 30% N and 6% S					
N dose (kg ha ⁻¹)	150	43.8	47.5	55.5	48.9
	200	39.2	45.5	49.1	44.6
	250	31.1	40.4	50.3	40.6
Mean		36.2	41.9	49.6	42.6
LSD _{0.05} for:					
Treatment		2.2			
Year		1.3			
Treatment × year		3.9			

The value of physiological efficiency (E_p) under N fertilization varied from 16.3 kg to 29.4 kg kg⁻¹ N, depending on N dose, the type of fertilizer, and the year of research (Table 5). The highest mean E_p value was recorded in the third year of the experiment, then in the first year, and the lowest value was recorded in the second year of the experiment. When analyzing mean values for three years of research, significantly the highest values were obtained after fertilization with 150 kg N ha⁻¹ (regardless of the type of fertilizer)—values from the range 26.7–27.9 kg kg⁻¹ N. For 200 kg N ha⁻¹, supplementing N fertilization with S fertilization (as fertilizer B) increased the E_p .

Szmigiel et al. [60] showed that N fertilization at a dose of 60 kg N ha⁻¹ increased the E_p to the maximum, and higher N doses (120 kg and 150 kg N ha⁻¹) decreased the E_p . Velasco et al. [64] also recorded a decrease in the E_p with increasing N doses. Klikocka et al. [52] presented that the addition of sulfur at a 50 kg ha⁻¹ dose to nitrogen dose of 40 kg ha⁻¹ resulted in the E_p amounting to 21.6 kg kg⁻¹ N. Compared to the variant without S addition, that was a 1.5-fold increase. However, Salvagiotti et al. [51] stated that wheat fertilization with various N and S doses did not increase the E_p value under different weather conditions, and explained that this factor presents low variation under variable environmental conditions.

Table 5. Physiological efficiency of N fertilization of winter wheat (kg kg⁻¹ N).

Treatment	Year			Mean	
	2015	2016	2017		
Ammonium nitrate: 34% N					
N dose (kg ha ⁻¹)	150	25.7	29.2	28.9	27.9
	200	25	16.4	24.8	22.1
	250	16.3	19.7	24.7	20.2
Fertilizer A: 26% N and 13% S					
N dose (kg ha ⁻¹)	150	27.7	28.2	27.6	27.8
	200	21.4	16.7	24.9	21
	250	20.7	17.5	23.7	20.6
Fertilizer B: 30% N and 6% S					
N dose (kg ha ⁻¹)	150	27.4	21.5	31.1	26.7
	200	21.7	22.9	29.4	24.7
	250	18.1	19.3	24.4	20.6
Mean	22.7	21.3	26.6	23.5	
LSD _{0.05} for:					
Treatment	1.2				
Year	0.7				
Treatment × year	2				

Optimization of N fertilization of crops (providing accomplishment of agronomic, economic, and environmental goals) still constitutes a challenge for science and agricultural practice [65]. Efficient management of N fertilization is a pivotal factor for maintaining economical crop production and long-term environmental quality. It should combine the dose, form, and time of N application in a way that optimizes the quantity and quality of crop yield, at the same time minimizing nutrient losses [19,64,66]. Excessive doses of nitrogen are often applied in hopes of increasing wheat grain yield [67]. However, an increase in wheat grain yield is not linearly linked to an increase in N dose. Additionally, unsuitable management of nitrogen fertilizers poses many environmental hazards [68,69]. Due to the fact that world population is still growing, global food production must keep pace with it. Over 40% of the global population's food needs are supplied by N fertilizers, and it is estimated that in future this value will increase at least to 60%. However, it is assessed that only 30–50% of nitrogen applied worldwide is taken up by crops. In the most intensive agricultural production systems, the amount of the unused nitrogen may reach over 50% and up to 75% of the N applied, the element is lost by leaching into the soil profile [54,70]. From an exclusively economic point of view, it is estimated that a 1% improvement of N efficiency in cereals could save over US\$200 million in N fertilizer costs, worldwide [71]. Therefore, fertilizing crops with excessive N rates not only poses environmental hazards, which is gradually becoming a serious cause for concern, but also leads to economic losses [44,54,71–74].

Due to the fact that sulfur is an essential component of enzymes involved in nitrogen metabolism, supplementing N fertilization with sulfur can bring measurable benefits [51]. Concurrent management of N and S may reduce the potential pollution of residual soil nitrates by increasing N uptake and recovery and by maintaining a high level of N efficiency.

In the conducted research, the same doses of N and S were introduced with fertilizers A and B. The beneficial effect of fertilizer B (containing 30% N and 6% S) may be explained by a uniform composition of each fertilizer granule, adapted to the requirements of cereals (it is assumed that,

for 1 t of grain and a corresponding amount of straw, 22–34 kg N and 3.0–5.2 kg S are needed [75]). In treatments with fertilization with fertilizer A, due to the high content of sulfur in that fertilizer (26% N and 13% S), the nitrogen dose was supplemented with ammonium nitrate (two fertilizers were the source of N). The composition of fertilizer granules differed, therefore the amount of N and S, which the plants had direct access to, might not have always strictly corresponded with the requirements of wheat.

Next to nitrogen availability, the most significant factors affecting wheat grain quality and quantity also include climatic conditions [76–79]. Despite the ongoing advancement of agrotechnology and improvement of crop varieties, weather is still the main uncontrolled factor affecting agricultural production [78,80]. Wheat is sensitive to high temperatures which enhance the level of water stress in plant cells. The optimum temperature range for the early growth phases of wheat is 12–25 °C, while 35.4 °C is critical temperature for the grain-filling phase [79]. Global wheat production is assessed to decrease by 6% for each Celsius degree increase in temperature [81]. Optimal humidity conditions during vegetation period are also important, higher temperatures associated with decreasing humidity cause the lack of water and thus decrease the yield. Even during sowing, low soil water content and low precipitation slow down the germination process, decrease the percentage of germinated grains, and hence plant density [82]. Water requirement during the growing season of winter wheat ranges from 400 to 650 mm [80,83,84]. However, Rossini et al. [27] noted that under various weather conditions, wheat yield is influenced by N fertilization rate only when the amount of rainfall exceeds 450 mm over the growing season. As the authors pointed out, an adverse effect of decreasing rainfall amount on wheat grain yield resulted from the impact on the number of kernels per spike and mean kernel weight. Fertilization with the same N dose may affect in different ways, and the determined decrease in wheat yield may be a response to the interaction of external biotic and abiotic factors [85].

4. Conclusions

The analyzed parameters depended greatly both on the treatment and year of the experiment (in other words on weather conditions).

When analyzing mean values for three years of research, the highest optimal nitrogen dose and maximum yield were recorded for the application of the new fertilizer available on the Polish market and designed for cereals cultivation (a mixture of ammonium nitrate and ammonium sulfate, containing 30% N and 6% S). For that fertilizer, optimal nitrogen dose amounted to 217 kg N ha⁻¹, and maximum yield amounted to 8251 kg ha⁻¹.

Significantly the highest agronomic efficiency and physiological efficiency of nitrogen fertilization, as well as the highest apparent nitrogen recovery were obtained after fertilization with 150 kg N ha⁻¹ than after fertilization with 200 kg and 250 kg N ha⁻¹.

However, compared to nitrogen fertilization without sulfur, sulfur fertilization increased the nitrogen recovery. Sulfur supplementation with the new fertilizer also significantly increased the agronomic efficiency (for 200 kg and 250 kg N ha⁻¹) and physiological efficiency (for 200 kg N ha⁻¹) of nitrogen fertilization of winter wheat.

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