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ORIGINAL PAPER

Nitrogen management impact on winter triticale grain yield and nitrogen use efficiency*

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Abstract

The soaring prices of nitrogen fertilizer production, low use efficiency of nitrogen compounds, and environmental threats resulting from soil nitrogen leaching and gaseous nitrogen losses are the main reasons for conducting research on increasing nitrogen use efficiency (NUE). The aim of the study was to assess the effect of foliar application of the new generation of N fertilizers in the second and third dose on the yield of winter triticale and grain protein content, and to evaluate the indicators of nutrient efficiency: agronomic efficiency and apparent nitrogen recovery, relative to fertilizer type and method of application. The experiment was set up as a single factor one with a complete randomized block design. The experimental factor was the varying dose of mineral nitrogen fertilization against the constant level of phosphorus and potassium application. According to the experimental design, two liquid fertilizers (A1N and A2N) applied to foliage were the source of nitrogen in the second and third doses of fertilization, except for the control treatment (AN). The use of the hybrid technique of nitrogen application in the triticale fertilization technology at the same time reduced N fertilizer doses by 20 and 25% and significantly enhanced the yield of grain. Moreover, the treatment with the tested fertilizers increased significantly the nitrogen use efficiency from 45% to 75%. Considering the average protein contents from four experiments, the reduction in nitrogen doses, irrespective of the liquid fertilizer used, resulted in a decline in the grain protein content compared to the control. The results demonstrate the possibility of meeting the legal requirements for reducing the nitrogen dose while ensuring the yield at the same or even an increased level.

Keywords: nitrogen fertilizers, method top-dress N application, foliar fertilization, protein content, nitrogen use efficiency

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INTRODUCTION

Winter triticale is the second grain crop in yields, after wheat, grown in Poland. Domestic cropping of winter triticale ranks 1/3 of the worldwide yields and more than 40% of the EU production (FAOSTAT 2023). Since triticale grain is mostly used for producing animal feeds, it affects the economic conditions of animal production. Thus, the major demand for feed grain stems from the fodder industry, particularly from poultry farming, and more recently from cattle and pig farming. As reported by the Central Statistical Office in Poland, the acreage of winter triticale in Poland was between 1.3 and 1.5 million ha, which amounted to about 18% of the national grain cropping surface (GUS 2022). The main reasons behind the popularity of triticale cropping include its higher yield potential on less fertile sites as compared to wheat, combined with the higher resistance to soil acidification, leaf diseases, abiotic factors, and the requirements relative to preceding crops (Feledyn-Szewczyk 2020, Jańczak-Pieniążek 2023).

The actual yield of a crop plant is a result of several factors, including cropping system advancement, production inputs (high rates of nitrogen fertilization, a high level of crop protection), precipitation distribution throughout the growing season, and the efficiency of nitrogen use (Brevik 2013, Taiz 2013, Iizumi 2015). Dawson and Hilton point out that if no nitrogen fertilization had been applied, half of the world's population would have starved today due to the lack of food (Dawson, Hilton 2011). Implementation of appropriate agrotechnical treatments aims at obtaining yield that will be as close as possible to the standard yield, or even at obtaining yield above standard.

The nitrogen application dose required for the desired productivity level for a given crop is lower than the actual nitrogen application dose. Excess nitrogen in the soil is primarily removed through plant assimilation, substrate absorption, and other losses, such as ammonia volatilization and N_2O and N_2 emissions from simultaneous nitrification and denitrification (Wu et al. 2013, Wang et al. 2016). Improving crop production, soil health, and the economic and environmental aspects requires good fertilizer N management practices (Erisman et al. 2018). According to Faber and Jarosz, the N losses as ammonia from mineral fertilizers may range from 0.5 to 40% of the total nitrogen amount applied, and depend primarily on the fertilizer application method (Faber, Jarosz, 2018). Following the data from the National Centre for Emissions Management, nitrogen fertilizers are responsible for 17% of the discharged volatile ammonia (KOBiZe 2019).

The intensification of agricultural production has a profound impact on climate change due to the emission of greenhouse gases (GHG), as was reported by the IPCC (IPCC 2014). Considerable quantities of greenhouse gases are emitted from fuel combustion during agrotechnical works, while these amounts depend largely on the cropping system, crop rotation, type of agrotechnical treatment, type of machinery, and fertilizers applied, including mainly nitrogen fertilizers (Rybacki, Gaj 2022, Winkhart et al. 2022). The European Commission has taken several legislative actions aimed at sustainable nitrogen management. Among them, the Nitrate- and National Emission Ceilings (NEC) Directives were implemented (EEC 1991, European Union 2016). The above measures are intended to achieve the national emission reduction commitments for five important air pollutants, including nitrogen oxides, and to protect water quality across Europe by preventing nitrates from agricultural sources from polluting ground and surface waters, and by promoting the use of good farming practices. Thus, it is of great significance to meet these assumptions while ensuring appropriate quantities and quality of yields.

Optimizing N management is critical to improving N productivity in the context of over-fertilization seen currently in European agricultural practices. The best management practices include applying the right nutrient source at the right time, in the right amount, and in the right place, collectively known as the 4R's Principle (Majumdar et al. 2013, Lal 2016). This approach ensures that improvements to the nutrient use efficiency of the components contribute toward improving the efficiency of the system. The widespread practice of nitrogen fertilization of grain crops relies on using solid conventional fertilizers, whose use efficiency is low, in particular when combined with water deficiency at heading and watery ripe stages. The absorbing capacity and nitrogen use efficiency are significantly affected by the element's sources and forms (Gruffman et al. 2014, Uscola et al. 2014) and closely related to its internal transportation and distribution (Tang et al. 2020).

Increased production and improvement of the element use efficiency from fertilizer may be obtained by changing the method of fertilizer application (Lal 2016, Dhillon, Raun 2020). An alternative to classic, solid nitrogen fertilizers is a new group of fertilizers available on the market, containing nitrogen in three forms (ammonium, nitrate, and amide), additionally enriched with amino acids obtained from algae, and compounds with properties that allow drops to adhere very well to the surface of leaf blades after the treatment, and slow drying substances, which ensures greater efficiency of the products. An advantage of such fertilizers is their high flexibility of use at each stage of cereal development, and the possibility of combining fertilizers with pesticides and growth regulators. Such a solution in agricultural practice is of particular importance both for economic and environmental reasons, as it entails fewer passes of machinery on a field, which also diminishes the carbon footprint (Rybacki, Gaj 2022). Foliar supplementation, for example, is more environmentally friendly, immediate, and target-oriented than soil fertilization since nutrients can be directly delivered to plant tissues during critical stages of plant growth (Fernandez et al. 2013). Another factor that should be considered is the lack of synchrony between the quantity of N released from fertilizers and the dynamics of N acquisition by crops. As has been reported by numerous national and foreign authors, this problem may be solved by nitrogen dose partitioning to best satisfy the needs of a given crop over time (Snyder et al. 2014, Sosulski et al. 2014).

The soaring prices of nitrogen fertilizer production, low use efficiency of nitrogen compounds, and environmental threats resulting from soil nitrogen losses via leaching and volatilization were the reasons for undertaking hitherto study and formulating the following research questions: (1) is it possible to replace solid conventional nitrogen fertilizers with the new nitrogen fertilizers applied by foliar spraying on triticale plants? (2) is it possible to improve grain yields and the efficiency of nitrogen use with the addition of sulfur and amino acids from marine algae present in fertilizer A2?; (3) is it possible to obtain comparable yield and protein content in grain with a reduced dose of nitrogen applied by foliar spraying? Bearing in mind the above questions, it was hypothesized that foliar application of nitrogen using a new generation of nitrogen fertilizers applied at a dose reduced by 20 and 25% compared to the optimal nitrogen dose would not reduce the grain yield of winter triticale. Thus, the present study was undertaken to (1) assess the effect of foliar application of the new generation of N fertilizers in the second and third dose on the yield of winter triticale and grain protein content, and (2) evaluate the indicators of nutrient efficiency: agronomic efficiency and apparent nitrogen recovery, relative to fertilizer type and method of application.

MATERIALS AND METHODS

The tested material

The fertilizers studied were formulated in the new generation of formulations containing a synthetic latex rain-fastening agent (styrene-butadiene copolymer), this added additional humectant properties. Compared to fertilizer A1 (without S), fertilizer A2 was additionally enriched with carboxylic acids, free amino acids and growth hormones derived from partly fermented extract of Atlantic algae. Sulphur in A2 fertilizer was present in the thiosulphate form, in the amount of 68 g L^{-1}, which was equivalent to 27 g S L^{-1}. According to the manufacturer's recommendation, spraying was carried out with a sprayer equipped with medium and fine drop nozzles. Foliar application was carried out using an AMAZONE UX 4200 sprayer, equipped with two-stream nozzles with a diameter of 0.3 mm.

The total N content in both fertilizers (A1 and A2) was 330g L^{-1}, including three nitrogen chemical forms, such as ammonia – 8.75%, nitrate – 8.75%, and amide – 16.5%. The final chemical formulation of the fertilizers was refined as part of the ongoing project PIOR.02.03.02.30-0026/16 co-financed by the European Union funds in 2017-2018. The formulation refinement aimed to achieve two objectives: firstly to further reduce the scorch risk when diluted at more than 20:1, and secondly to try and create a formulation that was cheaper to produce.

Experimental design

A series of four field trials with winter triticale cv. Tadeus were conducted at a private experimental field in Gądków Wielki, in the western part of the Lubuskie voivodeship (52°14′N, 14°58′E). The experiment was carried out for two consecutive years, i.e. 2019 and 2020, on two fields differing in preceding crops applied. Winter rapeseed was the preceding crop on the first field, and winter wheat – on the second field.

The soil type was lessive soil developed from loamy sand, classified as a good rye complex. The experiment was conducted on Albic Luvisol (IUSS, 2022), formed from glacial till, with Ap, Et, Bt, BC, C horizon sequence in soil profile, and sandy loam (18% of clay) texture in the ploughing horizon. The soils used in the study were rich in available phosphorus (68-75 mg P kg^{-1} of soil), contained medium levels of potassium (150-177.6 mg K kg^{-1}) and had a low content of available magnesium (37.1-80 mg kg^{-1}). The soil reaction was slightly acidic (pH 6.0-6.1 1M KCl).

The experiment was set up as a single factor with a randomized complete block design. The experimental factor was the varying dose of mineral nitrogen fertilization against the constant level of phosphorus and potassium application. Phosphorus and potassium doses were the same in every year of study, and amounted to 21.8 kg P and 74.7 kg K ha^{-1}, respectively. Before seeding winter triticale, a single dose of multicomponent fertilizer as a source of P and K was applied. The nitrogen dose was determined based on the assumptions of the nitrate programme in line with the Decree of the Council of Ministers of June 5 2018 (Journal of Laws as of July 2018, item 1339, as amended).

Experimental treatments

The treatments of the field trials are shown in Table 1. A reference point for assessing the effectiveness of the new-generation nitrogen fertilizers was the treatment with ammonium nitrate (34% of N) applied as top dressing on three designated dates. The total N dose in this treatment (AN ammonium nitrate) was 180 kg N ha^{-1}. The N doses in the remaining treatments were reduced by 20% and 25%, respectively, as compared to the AN treatment, and amounted to 144 and 135 kg N ha^{-1}, respectively. Nitrogen was applied at the beginning of spring vegetation BBCH 20/21, at the beginning of the stem elongation phase BBCH 30/31 and before heading (BBCH 51/55). 70 kg N ha^{-1} of ammonium nitrate was applied in each treatment as a first dose of N fertilization. The N doses on the succeeding dates depended on the treatment type and amounted to 60 (AN), 37 and 32.5 kg N ha^{-1}, respectively. To avoid potential phytotoxicity caused by high concentrations

Table 1

Nitrogen fertilization scheme for winter triticale

No.	Treatment abbreviation	I application (kg N ha^{-1})	II application (kg N ha^{-1})	III application (kg N ha^{-1})	Total nitrogen dose (kg N ha^{-1})
1	AN	70	60	50	180
2	A1N20	70	37	37	144
3	A1N25	70	32.5	32.5	135
4	A2N20	70	37	37	144
5	A2N25	70	32.5	32.5	135

of fertilizers, the N doses were partitioned between two applications at 7-day intervals.

To calculate the efficiency indices of nitrogen capture from fertilizers, an absolute control with no fertilizer treatment was also set up. According to the experimental design, two liquid fertilizers (A1N and A2N) applied to foliage were the source of nitrogen in the second and third doses of fertilization, except for the control treatment (AN). The II and III doses of nitrogen were determined based on the assessment of the nutrition status of winter triticale. The plant N content was evaluated at the beginning of the stem elongation phase (BBCH 30/31 phase). The assessment of the plant's N nutrition status showed the optimal foliar N content compared to the normative values in each year of the study (detailed assessment of the plant's nutritional status available from the authors). Every treatment was analyzed in four replications, totaling 20 experimental plots of 80 m^2 for the whole experiment. The grain at the stage of full maturity was harvested from the surface of 50 m^2 using a combine. Additionally, two separate 0.5 m^2 areas near the center of each plot were harvested manually. The biomass of straw and grains was separated and oven-dried at 60°C to determine grain yield and standardized to 14% moisture. All the herbicide and fungicide treatments were conducted according to the classical agrotechnical principles of growing winter triticale.

Weather conditions

The local climate, classified as intermediate between the Atlantic and continental climates, is seasonally variable, particularly in summer. Meteorological conditions varied over the study period. To compare the level and distribution of precipitation and temperatures, the data from the study year were juxtaposed against those from 1991–2020. Humidity and thermal conditions during the experiment are shown in Figure 1. The weather conditions varied over the growing seasons. The precipitation sum was 382 mm for the first growing season (2018/2019), and 369 mm for the second one (2019/2020) – Figure 1.

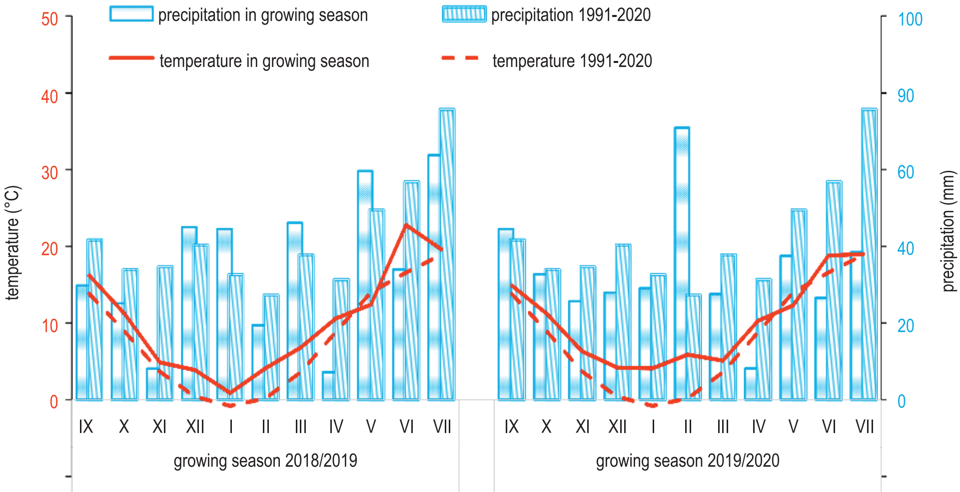

Fig. 1. Weather conditions during consecutive months of three seasons of winter triticale growth

Chemical analysis of plant material

The plant material was prepared for laboratory determination of nutrient contents. About 100 g subsamples of grain and straw were taken and ground with a stainless-steel grinder. The nitrogen (N) and sulphur (S) contents were determined with a Vario MAX cube CNS elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany.

Nitrogen and sulfur uptake was calculated by multiplying the quantity of yield (of grain and straw) and the N or S content in that yield (arithmetic means of the N content in the yield for a particular treatment and for a particular year of the experiment were used; the grain N uptake = % N in grain × grain yield), and the straw N uptake = % N in straw x straw yield). The nitrogen yield index (NHI) and sulfur yield index (SHI) were calculated as:

$$NHI = UNg/UNtot\ (\%) \quad (1)$$

$$SHI = USg/UStot\ (\%) \quad (2)$$

where: UNg – nitrogen uptake by grain at the time of harvest (kg ha^{-1}), UNtot – the total nitrogen uptake by plants at the time of harvest (kg N ha^{-1}), USg – sulphur used by grain at the time of harvest (kg ha^{-1}), UStot – the total sulfur used by plants at the time of harvest (kg S ha^{-1}) – Fageria (2014).

Nitrogen agronomic efficiency (NAE) is a parameter that defined the plant yield increase in a given range of nutrient doses (NAE kg – the crop yield increase per kg nutrient applied). The agronomic efficiency (NAE) of nitrogen fertilization of winter triticale was calculated according to the equation (3), after Folina et al. (2021):

$$NAE = Y - Yo \text{ (kg kg}^{-1}\text{ N)} \quad (3)$$

where: NAE – the agronomic efficiency of nitrogen fertilization (kg kg^{-1} N), Y – the yield of fertilized plants (kg ha^{-1}), Yo – the yield of control plants – unfertilized (kg ha^{-1}).

Apparent nitrogen recovery (ANR) was calculated as:

$$ANR = U - Uo/D \times 100 \text{ (\%)} \quad (4)$$

where: ANR – apparent nitrogen recovery (%), U – nitrogen uptake by fertilized plants (kg N ha^{-1}), DN – nitrogen dose (kg N ha^{-1}) – Folina et al. 2021.

Statistical analysis

A fixed-effects model of a three-way ANOVA with a general linear model according to the split-split-plot design (SPP) was applied to determine the combined effect of nitrogen fertilizer, preceding crop and study years, and the effects of their interactions on the grain yield (GN), grain protein content (GPC), total nitrogen uptake (TNUp), apparent nitrogen recovery (ANR), nitrogen agronomic efficiency (NAE), nitrogen harvest index (NHI), total sulfur uptake (TSUp) and sulfur yield index (SHI). The main-plot factor was study years (A), the sub-plot factor was preceding crop (B), and the sub-sub-plot factor was the combined effect of nitrogen fertilization (C) (Pritschet et al. 2016). Homogenous groups were determined using the Tukey HSD test at P=0.05. In order to examine the differences between the fertilizers, irrespective of the nitrogen dose, a simple contrast analysis was used. Calculations were made using Statistica 12.0 software (TIBCO, Palo Alto, CA, USA). The graphs were made in Excel within the OFFICE 365 package. Eta squared was used to gauge the effect size for the ANOVA model.

RESULTS

Grain yield

The grain yield response of winter triticale to the new type and level of nitrogen fertilization was ambiguous and variable across the study years. A three-way ANOVA revealed that there was a statistically significant interaction effect between the study years and treatment types on the triticale grain yield [$F(4, 48) - 30.84$, $p<0.001$, $\eta^2 - 0.162$] – Table 2. The effect explained 16.2% of the variability of the results, whereas the effect of the remaining interactions between the experimental factors was insignificant.

In 2020, the highest grain yield of triticale, regardless of the fertilizer tested, was recorded for treatments where the N dose was reduced by 20% compared to the control (Figure 2). In the treatments with the N dose reduced by 25%, contrary to the previous year, the application of both fertilizers resulted in a downward trend, but a greater difference was noted

Table 2

F- statistics and eta squared of ANOVA for the years-A×B×C type SPP design for grain yield (yield), protein content (protein), total nitrogen uptake (TUpN) and total sulfur uptake (TUpS)

Source of variance	Df_1	Df_2	Yield		Protein		TUpN		TUpS	
			F	η^2	F	η^2	F	η^2	F	η^2
Year (A)	1	3	9.53^{ns}	8.9	11.39*	8.5	242.41***	42.1	53.44**	34.7
Preceding crop (B)	1	6	195.14***	17.8	< 1^{ns}	< 1	69.73***	5.8	16.78**	8.7
Treatment (C)	4	48	82.38***	43.2	25.13***	37.3	4.72**	4.7	1.34^{ns}	2.4
A×B	1	6	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	< 1
A×C	4	48	30.84***	16.2	16.96***	25.2	28.23***	28.1	9.66***	17.6
B×C	4	48	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	1.3
A×B×C	4	48	< 1^{ns}	< 1	< 1^{ns}	1.1	< 1^{ns}	< 1	2.06^{ns}	3.8

Df_1 – degrees of freedom for the effect, Df_2 – degrees of freedom for the corresponding error, η^2 – eta squared (%), *** significant at p<0.001, ** significant at p<0.01, * significant at p<0.05, ns – not significant.

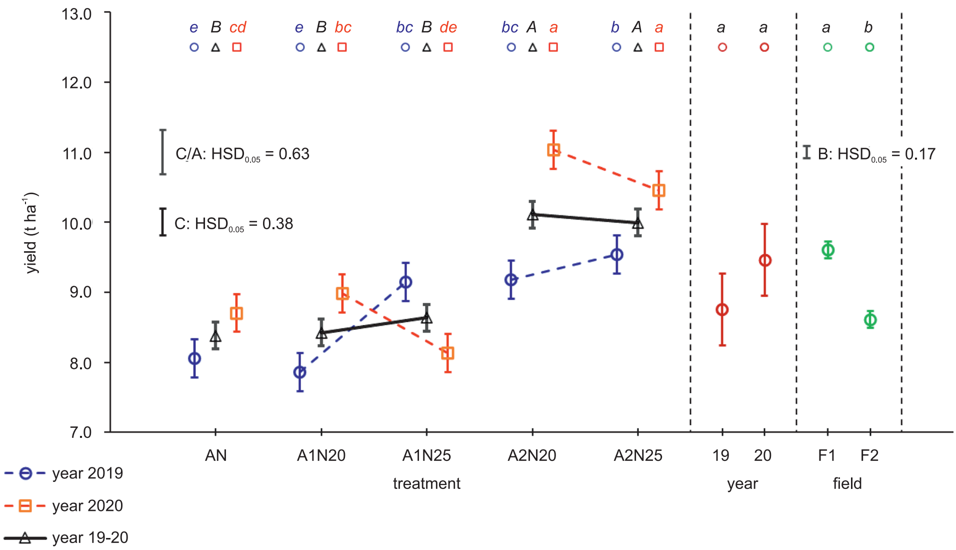

Fig. 2. Winter triticale grain yield depending on the experimental factors. Average yields labelled with different capital letters are significantly different depending on N fertilizers; yields labelled with different small letters are significantly different for interaction: study years and N fertilizers. Error bars denote 95% confidence intervals for means

for the treatments with A1 fertilizer. In turn, a simple analysis of the main effects showed a significant effect of treatments [$F(4, 48) - 82.38$, $p<0.001$, $\eta^2 = 0.432$] and preceding crop [$F(1, 6) - 195.14$, $p<0.001$, $\eta^2 = 0.178$] on the triticale grain yield, while the effect of the year was insignificant.

The yield of triticale grain averaged from four trials conducted in 2019-2020 was 9.11 t ha^{-1}. Among the three experimental factors examined, the fertilization type was primarily responsible for the variability of the size of grain yields, which is expressed by the value of the coefficient η^2 – 42.2% (Table 2). The effect of the other two factors, i.e. preceding crop and year of study, was smaller and amounted to (η^2 – 18.8% and η^2 – 8.9%), respectively.

The analysis of simple contrasts revealed that the average grain yield for the treatment with A2 fertilizer (M – 10.05, SD – 1.06) was significantly higher compared to the control (M – 8.38, SD – 0.70), [$F(1, 48) - 29619.42$, $p<0.001$] and the same was found for A1 fertilizer (M – 8.53, SD – 0.83) [$F(1, 48) - 253.84$, $p<0.001$). The differences for the abovementioned relationships were 20.0 and 17.9%, respectively. The average grain yield for the treatments with A1 fertilizer was comparable to the control [$F(1, 48) - 1.61$, $p = 0.211$].

Taking into account the influence of the preceding crop type as an experimental factor, it was found that sites where triticale was grown after rape produced a significantly higher average grain yield (M – 9.61, SD – 1.12) than those after wheat and the difference was 11.6% (M – 8.61, SD – 1.04).

Comparing the size of average yields depending on the study year, higher yields were recorded in 2020 (M – 9.46 t ha^{-1}, SD – 1.30) and the difference compared to 2019 was 8.1%, which quantitatively corresponded to 0.71 t ha^{-1} (M – 8.76 t ha^{-1}, SD – 0.96).

Protein content

The effect of treatments on the triticale grain protein content was also ambiguous and varied over the study years (Table 2).

Considering the grain protein content, the three-way ANOVA revealed a significant interaction effect between the years of study and treatments [$F(4, 48) - 16.96$, $p<0.001$, $\eta^2 - 0.252$). This effect explained 25.2% of the variability of the results. The effects of the remaining interactions between the experimental factors were insignificant.

In 2019, the highest grain protein was found for the treatment with optimal fertilization. Irrespective of the fertilizer used, the reduction of the N dose in the range of 20-25% compared to the control resulted in a significant decrease in the grain protein content (Figure 3).

In 2020, the grain protein content for the treatments with A1 fertilizer was at a similar level compared to the control, while in those with A2 fertilizer – there was a significant decrease in the grain protein content.

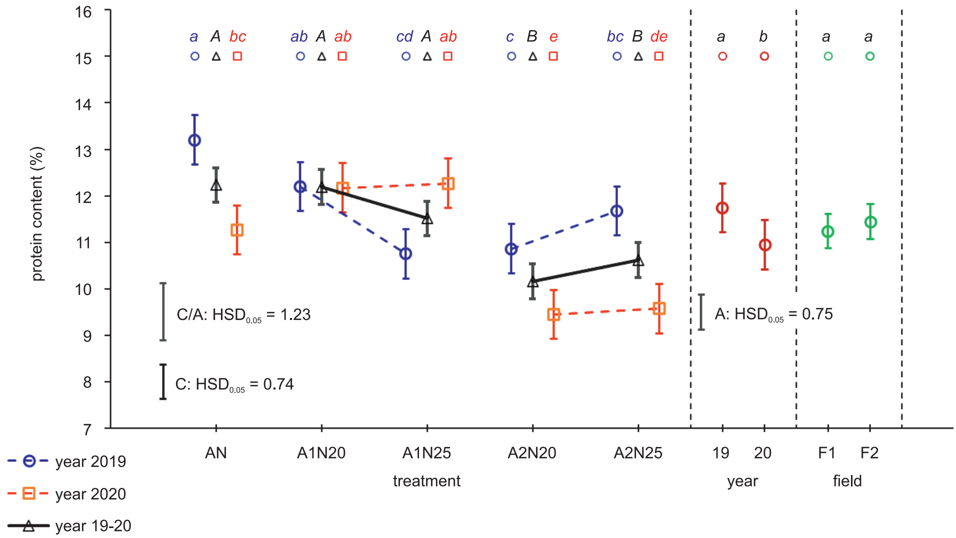

Fig. 3. Protein content depending on the experimental factors. Average protein content labelled with different capital letters are significantly different depending on N fertilizers; protein content labelled with different small letters differ significantly in interactions between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

In contrast, a simple analysis of the main effects showed a significant effect of the study years [$F(1, 3) – 11.39$, $p – 0.043$, $\eta^2 – 0.085$] and the treatments [$F(4, 48) – 25.13$, $p<0.001$, $\eta^2 – 0.373$] on the protein content. The influence of the third experimental factor, i.e. the preceding crop, on the variability of the grain protein content was insignificant [$F(1, 6) – 0.92$, $p – 0.374$, $\eta^2 – 0.006$].

The grain protein content averaged from the four field trials was 11.34% and was differentiated to the greatest extent by the treatment type, and to a lesser extent by the study years, which is expressed by the coefficients η^2, which are 37.3 and 8.5%, respectively.

The highest protein content in grain was found for the treatment with optimal N fertilization (M – 12.23, SD – 1.13). Reducing the nitrogen dose in the range of 20-25% compared to the control, irrespective of the fertilizer type, resulted in a decrease in the grain protein content. Significant differences in the protein content were also noted between sites fertilized with A1 and A2 fertilizers.

The analysis of simple contrasts revealed that compared to the control variant, the average grain protein content after applying A1 fertilizer (M – 11.85, SD – 1.18) did not differ significantly [$F(1, 48) – 2.86$, $p – 0.097$]. Significantly lower (by 1.84%) grain protein content compared to the control [$F(1, 48) – 65.86$, $p<0.001$] was found for A2 fertilizer (M – 10.39, SD – 1.08). The difference in the grain protein content for the sites fertilized with A2 and A1 fertilizers, respectively, was 1.46%.

Comparing the effect of the study year on the protein content, a significantly higher protein content in grain was found in 2019 (M – 11.74, SD – 1.15) and compared to 2020 (M – 10.95, SD – 1.47) the difference was 0.79%.

Total nitrogen uptake (TUpN)

Similarly to the case of grain yield, the effect of nitrogen treatments on the total N uptake by winter triticale at the stage of full maturity was ambiguous and variable across the study years (Table 2).

The three-way ANOVA performed for total nitrogen uptake showed a significant interaction effect between the study years and treatments [$F(4, 48)$ – 28.23, $p<0.001$, η^2 – 0.281). The effect explained 28.1% of the variability of the results. The other interactions between the experimental factors were insignificant (Figure 4).

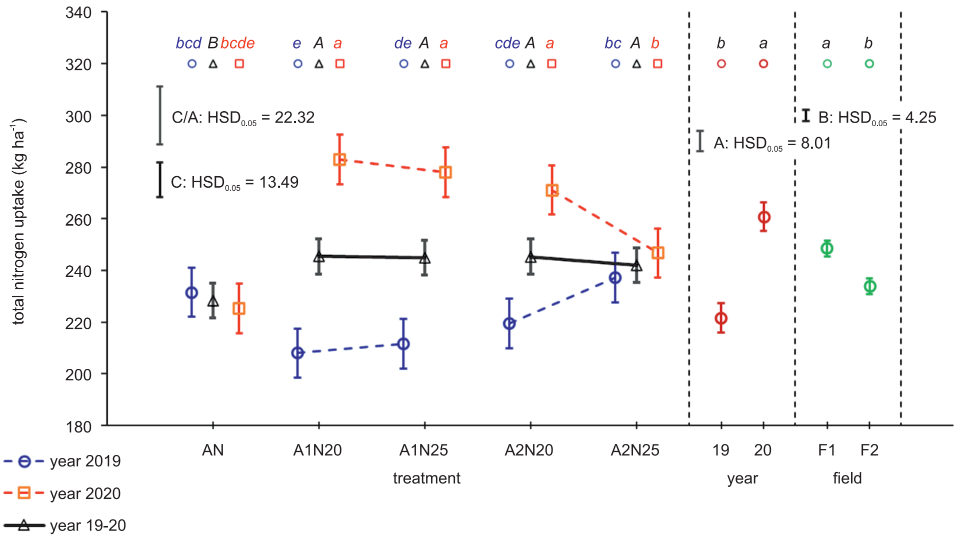

Fig. 4. Total nitrogen uptake (TNUp) depending on the experimental factors. Average TNUp labelled with different capital letters are significantly different depending on N fertilizers; TNUp labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

In 2019, the total nitrogen uptake compared to the control irrespective of the type of foliar fertilizer and the dose of fertilizer per area unit (1 ha), was at a similar level. However, in 2020, in the case of trials where A1 and A2 fertilizers were used, a significant increase in nitrogen uptake was found compared to the control (Figure 4). Greater fluctuations in the total nitrogen uptake over the study years were found for A1 fertilizer.

Considering the effects of the main experimental factors on shaping the total nitrogen uptake by triticale, the simple analysis revealed a significant effect of the study years [$F(1, 3)$ – 242.41, $p<0.001$, η^2 – 0.421], preceding crop [$F(1, 6)$ – 69.73, $p<0.001$, η^2 – 0.058) and treatment type [$F(4, 48)$ – 4.72, p – 0.003, η^2 – 0.047].

The nitrogen uptake averaged from the four trials was 241.21 kg N ha^{-1} and was determined to the greatest extent by the study years (η^2 = 42.1%), and to a lesser extent by the effect of the preceding crop and nitrogen fertilization type, which is expressed by the values of the η^2 index, 5.8 and 4.7%, respectively.

Comparing the values of N intake across the study years, a significantly higher N intake was found in 2020 (M – 260.80, SD – 26.46). The difference in N uptake compared to 2019 (M – 221.63, SD – 19.51) was 39.2 kg N ha^{-1}, which corresponds to 17.7%.

Considering the preceding crop effect in shaping the nitrogen uptake, a higher N uptake was found for triticale grown after rape (M – 248.46, SD – 28.54) than after wheat (M – 233.96, SD – 30.74). The difference in the amount of total N uptake depending on the preceding crop was 6.2%, which quantitatively corresponds to 14.5 kg N ha^{-1}.

Considering the values of N uptake averaged from four trials, a significant increase in N uptake was found due to the application of the A1 and A2 fertilizers compared to the control. The use of both the A1 and A2 fertilizers, even in reduced doses, led to a significant increase in nitrogen uptake compared to the treatment with optimal nitrogen fertilization.

The analysis of simple contrasts showed that the average nitrogen uptake by triticale for the treatments using the A1 fertilizer (M – 245.16, SD – 38.89), [$F(1, 48)$ – 16.59, $p<0.001$] as well as the A2 fertilizer (M – 243.68, SD – 23.65), [$F(1, 48)$ – 13.77, $p<0.001$] was significantly greater than in the control (M – 228.38, SD – 18.74). The differences for the above relationships were 16.8 and 15.3 kg N ha^{-1}, respectively, while the difference in nitrogen uptake between A1 and A2 fertilizers was insignificant [$F(1, 48)$ – 0.20, p – 0.660].

Total sulfur uptake (TUpS)

As in the case of the previously discussed indicators, the effect of treatments on sulfur uptake at the full maturity phase was ambiguous and varied over the study years (Table 2).

The three-way ANOVA showed a significant effect of the interaction between the study years and the type of nitrogen fertilization on sulfur uptake at full maturity [$F(4, 48)$ – 9.66, $p<0.001$, η^2 – 0.176] and this effect explained 17.6% of the variability of the results. The interactions for the remaining experimental factors were not significant.

Considering the year factor, it was found that in 2019, regardless of the fertilizer type (A1 and A2), the reduction of N dose in the range of 20-25% positively affected sulfur uptake by triticale compared to the control object, though no significant differences were noted between the treatments (Figure 5). In 2020, unlike relationships were observed. Foliar application of both fertilizers at reduced doses led to a reduction in sulfur uptake compared to the control. Significant relationships were noted only for the treatments where the A1 fertilizer was applied.

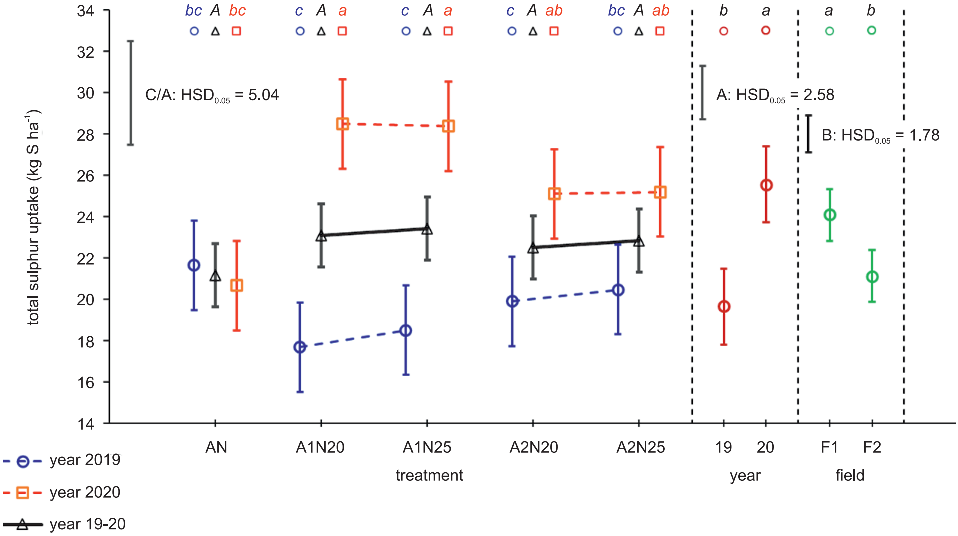

Fig. 5. Total sulfur uptake dependent on the experimental factors. Average TSUp labelled with different capital letters are significantly different depending on N fertilizers; TSUp labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

A simple analysis of the main effects showed a significant effect of the study years [F(1, 3) – 53.44, *p* – 0.005, η^2 – 0.347] and of the preceding crop on sulfur uptake [*F*(1, 6) – 16.78, *p* – 0.006, η^2 – 0.087]. The factor of differentiated N fertilization was insignificant in shaping the variability of sulfur uptake [F(4, 48) – 1.34, *p* – 0.269, η^2 – 0.024]. The sulfur uptake averaged from four trials was 22.61 kg S ha^{-1} and was determined to the greatest degree by the study years (η^2 – 34.75) and to a much lesser extent by the preceding crop (η^2 – 8.7%).

Significantly higher values of S uptake were found in 2020 (M – 25.57, SD – 4.43) than in 2019 (M – 19.65, SD – 3.78) and the difference was 5.92 kg S ha^{-1}, which corresponds to 30.2%.

Considering the preceding crop factor, the total sulfur uptake by triticale grown after rape (M – 24.10, SD – 5.79) was significantly higher than after wheat (M – 21.12, SD – 3.73). The quantitative difference in sulfur uptake depending on the preceding crop was 2.98 kg S ha^{-1}, which is equivalent to 14.1.

Nitrogen harvest index (NHI)

The three-way ANOVA revealed that there was a statistically significant interaction effect between the study years and treatment types on the NHI index [F(4, 48) – 24,10, p<0,001, η^2 – 0,120]. [F(4, 48) – 30.84, p<0.001, η^2 – 0.162]. The effect explained 12% of the variability of the results, whereas the effect of the remaining interactions between the experimental factors was insignificant (Table 3).

Table 3

F- statistics and eta squared of ANOVA for the years-A×B×C type SPP design for grain yield (yield), protein content (protein), total nitrogen uptake (TUpN) and total sulfur uptake (TUpS)

Source of variance	Df_1	Df_2	ANR		ANE		NHI		SHI	
			F	η^2	F	η^2	F	η^2	F	η^2
Year (A)	1	3	86.67**	23.3	7.82^{ns}	9.2	573.10***	68.8	65.72**	44.2
Forecrop (B)	1	6	51.90***	5.4	129.10***	12.5	71.03***	3.2	< 1^{ns}	< 1
Tretament (C)	4	48	22.18***	25.1	113.09***	53.6	13.91***	6.9	2.97*	4.7
A×B	1	6	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	< 1	< 1^{ns}	< 1
A×C	4	48	23.35***	26.4	22.40***	10.6	24.10***	12.0	10.86***	17.0
B×C	4	48	< 1^{ns}	< 1	< 1^{ns}	< 1	1.38^{ns}	< 1	2.21^{ns}	3.5
A×B×C	4	48	< 1^{ns}	< 1	1.04^{ns}	< 1	2.65*	1.3	2.99*	4.7

Df_1 – degrees of freedom for the effect, Df_2 – degrees of freedom for the corresponding error, η^2 – eta squared (%), *** significant at p<0.001, ** significant at p<0.01, * significant at p<0.05, ns – not significant

In 2019, the NHI index (M – 81.2, SD – 2.2) was significantly higher compared to that in 2020 (M – 69.6, SD – 5.2) and the values of the analyzed index differed by 11.7%.

The effect of N treatments on the NHI index varied across the study years. In 2019, regardless of the type of fertilizer and nitrogen dose, the NHI values were at a level comparable to the treatment with optimal N fertilization (Figure 6). However, in 2020, regardless of the type of fertilizer and nitrogen dose, significantly lower values of the index were obtained compared to the control. In addition, a greater response to the N doses applied due to the study year was found for the A1 fertilizer.

The simple main effects contrast analysis showed a significant effect of the year of study [F(1, 3) – 573.10, p<0.001, η2 – 0.688], preceding crop [F(1, 6) – 71.03, p<0.001, η^2 – 0.032] and differentiated nitrogen fertilization [F(4, 48) – 13.91, p<0.001, η^2 – 0.069].

The average value of NHI from a series of four experiments was equal to 75.4%, and was determined to the greatest extent by years of study and to a much lesser extent by the nitrogen fertilization type and preceding crop, which is manifested by the coefficients η^2 of 68.8%, 6.9% and 3 .2%, respectively.

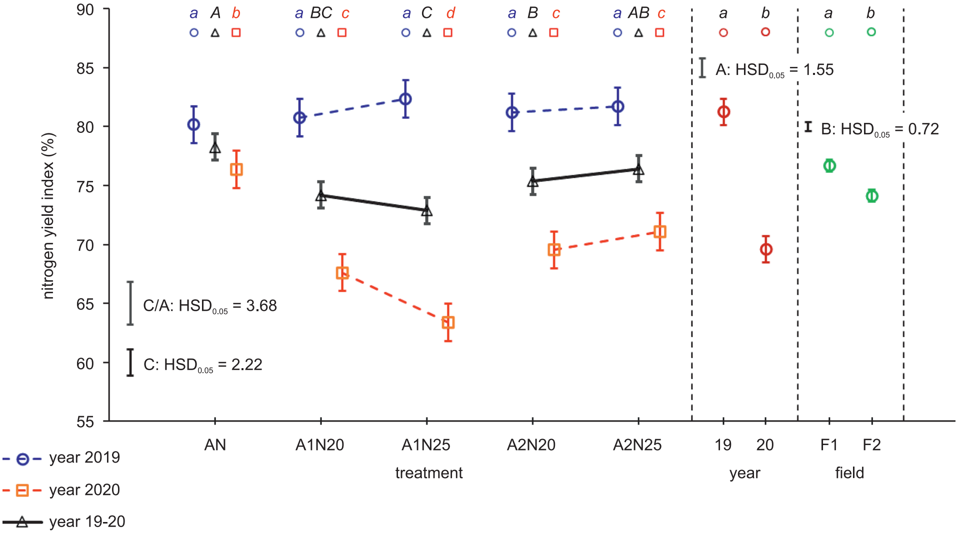

Fig. 6. Nitrogen harvest index dependent on experimental factors. Average NHI labelled with different capital letters are significantly different depending on N fertilizers; NHI labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

While comparing the values of NHI for the year of study, a higher value of NHI was observed in 2019 (M – 81.2, SD – 2.2) compared to that in 2020 (M – 69.6, SD – 5.2). The difference among years was 1.7%.

Considering the average value of NHI from four experiments, regardless of the type of fertilizer, the reduction of the nitrogen dose in the range of 20-25% compared to the control, led to a decrease in the value of the NHI index.

The analysis of simple contrasts revealed that the application of fertilizer A1 (M – 73.5, SD – 8.7) and A2 (M – 75.9, SD – 6.3) lead to a significant decrease in NHI, compared to the control (M – 78.3, SD – 2.9). The differences from the control were equal to 4.7% and 2.4%, respectively. The contrast between fertilizers A1 and A2 was significant [F(1, 48) – 18.09, p<0.001]. The highest value of NHI was obtained for fertilizer A2, and the difference between this fertilizer and fertilizer A1 was equal to 2.4%.

Considering the preceding crop as a factor, the NHI index after rape (M – 76.7, SD – 7.2) was significantly higher than after wheat (M – 74.2, SD – 6.7) and the difference for the above relationship was 2.5%.

Sulphur harvest index (SHI)

The influence of variants of fertilization on the SHI varied over the years. The three-way ANOVA revealed that there was a statistically significant interaction between the study years and variants of nitrogen fertilization on the SHI [F(4, 48) – 10.86, p<0.001, η^2 – 0.170]. This effect explained

17.0% of the variability of the results obtained. Other interactions between the experimental factors and possible second-order interactions between the experimental factors were insignificant (Table 3).

In 2019, the SHI index, regardless of the type of fertilizer and nitrogen dose, was at a similar level compared to the optimally fertilized variant. However, in 2020, the value of the SHI indicator was lower compared to the control, regardless of the type of fertilizer and nitrogen dose. Significant differences were found only for the A1 fertilizer (Figure 7).

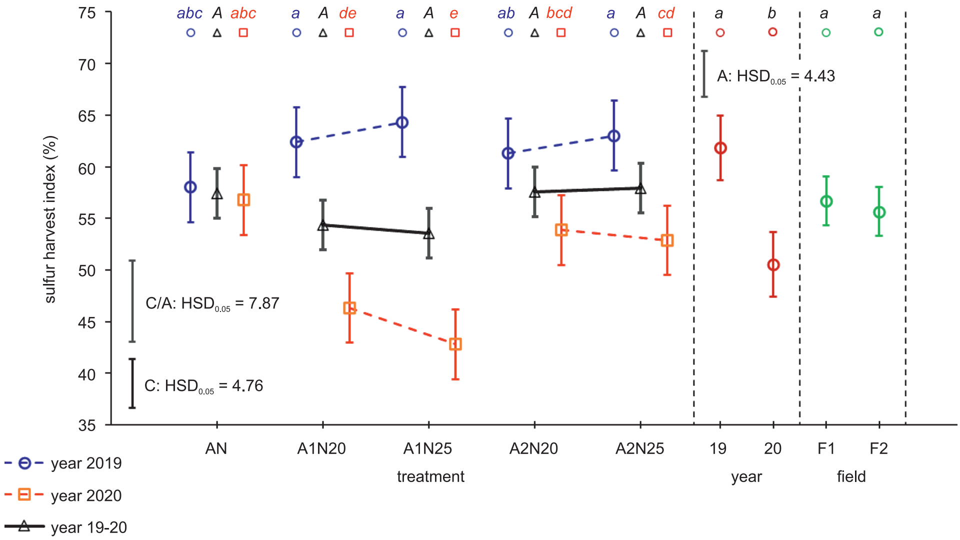

Fig. 7. Sulphur harvest index dependent on the experimental factors. Average SHI labelled with different capital letters are significantly different depending on N fertilizers; SHI labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

The simple main effects contrast analysis showed a significant effect of the year of study [$F(1, 3) – 65.72$, $p – 0.004$, $\eta^2 – 0.442$] and various nitrogen fertilization [$F(4, 48) – 2.97$, $p – 0.029$, $\eta^2 – 0.047$] on the value of the SHI. The influence of the preceding crop on the value of this index [$F(1, 6) – 0.56$, $p – 0.481$, $\eta^2 – 0.004$] was insignificant.

The average value of the SHI from a series of four experiments was equal to 56.2% and was determined to the greatest extent by years of study and to a much lesser extent by the nitrogen fertilization treatment, which is manifested by the coefficients η^2 of 44.2 % and 4.7%, respectively.

A significantly higher SHI was observed in 2019 (M – 61.8, SD – 5.9) compared to that obtained for 2020 year (M – 50.5, SD – 6.9) and the difference was 11.3%.

The analysis of simple contrasts considering the average values of the SHI revealed that the application of fertilizer A1 (M – 54.0, SD – 10.7) in a nitrogen fertilizer dose reduced by 20-25% led to a decrease in the SHI [$F(1, 48)$ – 5.61, p – 0.022] compared to the control (M – 57.4, SD – 7.5). As for fertilizer A2 (M – 57.8, SD – 6.0), the contrast was insignificant [$F(1, 48)$ – 0.06, p – 0.805]. A significantly higher SHI was found for A2 than for A1 fertilizer, and the difference was 3.8%.

Apparent nitrogen recovery (ANR)

The three-way ANOVA revealed a significant effect of the interaction between the study years and treatments with N fertilizers on differentiating the indicator of nitrogen recovery from fertilizers [$F(4, 48)$ – 23.35, p<0.001, η^2 – 0.264]. The effect explained the variability of the results at 26.4%. The remaining interactions between the experimental factors were insignificant (Table 3).

In 2019, the use of A1 fertilizer, regardless of the N dose, had no significant impact on the value of the nitrogen recovery indicator compared to the treatment with optimal N fertilization. A different effect was observed in the case of A2 fertilizer, as the reduction of the N dose in the range of 20-25% led to an increase in the nitrogen utilization rate, but significant differences were found only for the A2N25 treatment (Figure. 8).

In the second study year, a significant increase was found in the nitrogen recovery rate for both fertilizers (A1 and A2) applied in doses reduced in the range of 20-25% compared to the control.

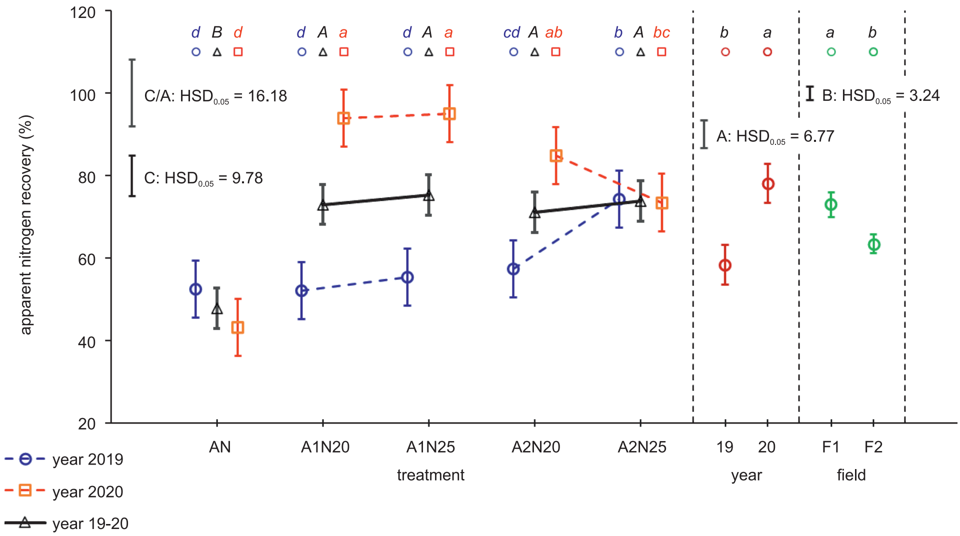

Fig. 8. Apparent nitrogen recovery dependent on experimental factors. Average ANR labelled with different capital letters are significantly different depending on N fertilizers; ANR labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

A simple analysis of the main effects showed a significant effect of the study years [$F(1, 3) – 86.67$, $p – 0.003$, $\eta^2 – 0.233$], preceding crop [$F(1, 6) – 51.90$, $p<0.001$, $\eta^2 – 0.054$] and treatment [$F(4, 48) – 22.18$, $p<0.001$, $\eta^2 – 0.251$] in shaping the variability of ANR.

Agronomic nitrogen efficiency (ANE)

The influence of variants of fertilization on ANE varied over the years. The three-way ANOVA revealed that there was a statistically significant interaction between the study years and variants of nitrogen fertilization on the ANE [$F(4, 48) – 22.40$, $p<0.001$, $\eta^2 – 0.106$]. This effect explained 10.6% of the variability of the results obtained. Other interactions examined were not significant.

In 2019, regardless of the type of fertilizer applied, the reduction of the N dose by 20-25% led to an increase in ANE. For A1 fertilizer, a significant increase was observed only when the dose was reduced by 25%, while for A2 fertilizer, an increase was observed for both reduced doses (Figure 9).

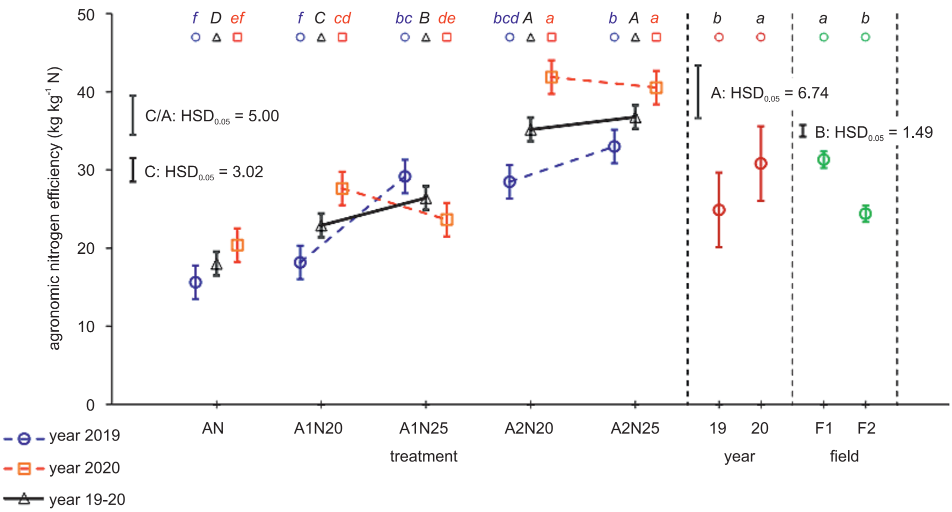

Fig. 9. Agronomic nitrogen efficiency dependent on experimental factors. Average ANE labelled with different capital letters are significantly different depending on N fertilizers; ANE labelled with different small letters are significantly different for interaction between the study years and N fertilizers. Error bars denote 95% confidence intervals for means

In 2020, the application of both fertilizers, regardless of N doses, resulted in an increase in ANE compared to the control. In the case of A1 fertilizer, a significant increase in ANE was observed only for the A1N20 treatment. Unlike in 2019, the application of the N dose reduced by 25% led to a decrease in ANE.

A simple analysis of the main effects showed a significant effect of the preceding crop [$F(1, 6) – 129.10$, $p<0.001$, $\eta^2 – 0.125$] and type of nitrogen fertilization [$F(4, 48) – 113.09$, $p<0.001$, $\eta^2 – 0.536$] on the value of ANE.

The average value of ANE from a series of four experiments was equal to 27.9 kg kg N and was determined to the greatest extent by the type of nitrogen fertilization, following the preceding crop and the study year, which is shown by coefficients η^2 of 53.6%, 12.5% and 9.2%, respectively.

The average values of ANE for fertilizers A1 and A2 applied in doses reduced by 20% and 25% compared to the control testify to a significantly increased use of nitrogen. Regardless of the fertilizer applied, higher values of ANE were observed for treatments A1N25 and A2N25.

A simple analysis of the main effects showed that ANE for A1 fertilizer (M – 24.6, SD – 6.7) and A2 (M – 36.0, SD – 8.0) was significantly higher compared to the control (M – 18.0, SD – 4.5). The value of ANE for the A2 fertilizer was significantly higher compared to A1. The difference was equal to 11.3 kg kg N, which was 45.9%.

While comparing the ANE value across the study years, it was found that ANE was significantly higher in 2020 (M – 30.8, SD – 10.0) than in 2019 year (M – 24.9, SD – 8.9) and the difference was 5.9 kg kg N.

Moreover, the forecrop also affected the value of ANE as a higher value of ANE was observed for rape (M – 31.3, SD – 9.6) than for wheat (M – 24.4, SD – 9.0) as a forecrop. The difference in this value was equal to 6.9 kg kg N, which corresponded to 28.4%.

DISCUSSION

Weather conditions

Differences in the results discussed below may result from weather conditions during the experiments in both years. As indicated in this section 2.4 and Figure 1, although the total precipitation in both years was practically the same, its distribution varied. The largest differences were observed in the months of March and May, which corresponds to a period of intensive triticale biomass growth. Overall, the 2019/2020 growing season was characterized by lower rainfall compared to 2018/2019. In March, the difference in the amount of precipitation was 46%, and in May it was 37%.

As for the overall sum of precipitation, it should be indicated that there are constant water-stress conditions resulting scarcity of precipitation, exacerbated by high air temperature. This might lead to occurrence of different stages of droughts (Pińskwar et al. 2020). Approximately one-third of the world's arable land is already water-stressed, with 12% of annual rainfall not exceeding 250 mm. In drought-affected agricultural areas, yield losses are typically up to 50%. The adverse impacts of climate change are felt across Europe in the form of heat waves and drought which is causing significant economic losses in the EU's agriculture sector. The same applies to the territory of Poland. In 2018-2019, generally in Poland, drought conditions were recorded, which of course could be variable at the level of individual regions (Pińskwar et al. 2020). Therefore, it is of key importance to look for methods to maintain the yield potential of plants.

Grain yield

From the perspective of the optimal utilization of the crop yield potential, a crucial element supporting the achievement of such a goal is the proper selection of N fertilizer, the date and technique of its application, as well as the selection of the right site. Malhi et al. highlighted an important point regarding the importance of synchronizing nitrogen fertilizer application with crop plant requirements (Malhi et al. 2006). This is because nitrogen is an essential nutrient for plant growth and development, and its deficiency can limit crop yields. The triticale grain yields obtained in our experiments exceeded more than twice the national average given by the Central Statistical Office in Poland. The average yield for winter triticale was 3.59 t ha^{-1} in 2019 and 4.5 t ha^{-1} in 2020, respectively, while the average yield obtained in our experiments was 9.11 t ha^{-1}, with a large variation depending on the fertilizer applied, forecrop and year of study. The value obtained should also be confronted with the value of yield achieved during the post-registration varietal testing conducted by the Research Centre of Cultivar Testing (COBORU) in Poland in 2019-2020 (COBORU 2021). The standard level for triticale under conditions of the average level of agricultural technology was 8.07 t ha^{-1} for 2019 and 8.29 t ha^{-1} for 2020, respectively. Considering the results obtained in our study, this means that in both the treatment with optimal N fertilization and the treatments with reduced N rates, the yield potential of triticale was utilized to more than 100%. Yield potential (Yp), as proposed by Evans and Fischer (Evans, Fischer 1999) defines the maximum attainable yield of a crop cultivar grown under conditions of the non-limiting supply of nutrients, and effective control of pests and diseases. Triticale, like wheat, is a cereal with a high production potential, thus one can expect harvests nearing the potential yield provided that sufficient water and nutrient supply is available. Conijn et al. reported that any increase in the production efficiency of both key agronomic factors, i.e., water and nitrogen, depends on the soil status of all the other production factors decisive for their efficiency (Conijn et al. 2018). In addition, we found that triticale grown on the site with a regulated pH, rich in available nutrients, fertilized at the right time with the use of a hybrid application technique, ensured grain yields in the range of 8.4 to 10.1 t ha^{-1}, i.e. significantly higher than the potential yields. In our study, the new-generation nitrogen fertilizers spread onto the foliage in the second and third rates significantly increased the triticale grain yield, which indicates their higher yield potential efficiency compared to the conventional solid fertilizer applied in three doses. Many researchers have noted the significance of split application in the optimization of yield and grain protein (Ottman et al. 2000, Woolfolk et al.

2002). In line with this, Ferrari et al. suggested that appropriate fertilizer application methods can promote crop growth and development, resulting in higher yields compared to using conventional nitrogen fertilizers alone (Ferrari et al. 2021). Compared to soil applications, where nitrogen is solubilized in the soil water solution and intercepted by plant roots, the benefits of foliar fertilization are linked to high absorption efficiency and mobility across plant tissues (Fernández et al. 2013). According to Zhang et al. (2007), and Wu et al. (2019) one potential reason for this result is that foliar fertilizers can improve nutrient absorption and transformation. Insufficient soil water affects the synthesis and transport of nutrients, reducing crop yield and quality. Appropriate application of fertilizers can increase chlorophyll content in plant tissues, as demonstrated by Xu et al. (2020). This promotes the growth of the above-ground parts, thereby increasing biomass accumulation. Results show that the forecrop had a significant impact on the grain yield (Figure 2), and oilseed rape was a better forecrop for high winter triticale production. The average grain yield was higher by 11.6% in the treatment where the forecrop was oilseed rape. The influence of different forecrops was widely studied (Yao et al. 2013, Mbuthia et al. 2015 Niewiadomska et al. 2020).

The rhizosphere zone after rapeseed cultivation contains a higher amount of available forms of phosphorus and microelements as compared to the rhizosphere zone after cereal cultivation (Town et al. 2023). Moreover, after harvesting rapeseed, a large amount of plant residues is ploughed into, thus providing the source of nutrients for the next crop. That is why we consider the role of the preceding crop as an important factor in increasing the yield of triticale grain in our experiment.

The solution adopted in the work, consisting of the use of the hybrid technique of N application in the technology of triticale fertilization, shows the positive effect of both fertilizers examined, although the performance of A2 fertilizer was significantly more efficient. The higher efficiency of A2 fertilizer was due to the content of both sulfur and amino acids. The beneficial effect of sulfur is widely known and well documented in the national and foreign literature (Klikocka et al. 2016, Rossini et al. 2018). Moreover, only a few scientific reports indicate the direct impact of amino acids applied together with mineral fertilizers on plant yield and quality parameters (Nardi et al. 2016, Miri Nargesi et al. 2022). The use of microalgae as biostimulants/biofertilizers in farming is still in its infancy because strategies for processing and applying algal material are yet to be developed and standardized (Gitau et al. 2022). Standardization of processing methods and formulation of these products are needed to ensure consistency and reliability of their performance (Lee, Ryu 2021).

The increase in the yield of triticale grain found for the treatments where foliar fertilizers were applied indicates that an essential agrotechnical factor determining the increase in yield, apart from the choice of fertilizer, is the proper technique of its application. When nitrogen is added only as a solid fertilizer, increasing doses of N do not always result in an increase in yield, which was also confirmed by Walsh et al. (2018). These researchers found no significant differences in wheat yield in response to the two levels of N fertilization, i.e. 90 and 135 kg N ha^{-1}. The best management practices include applying the right nutrient source at the right time, in the right dose, and in the right place, collectively known as the 4R's Principle (Roberts 2006). The technique of fertilizer application and the selection of appropriate chemical formulations are particularly important under conditions of recurring spring droughts, which most often occur in Poland during the phases of intensive biomass growth (from stem shooting to the end of heading). In our study, significant water deficits were noted in April in both the first and second study years (Figure 1). The 75% reduction in precipitation was noted compared to the regional multi-annual data. The water deficit was also partly noticeable in May and June, which was additionally accompanied by high temperatures. Unfavorable weather conditions in the abovementioned periods resulted in a different yield-producing response over the study years and high variability of the protein content. Liu et al. and He et al. highlighted that climatic change is one of the major factors intensifying abiotic stress on crops, which results in reduced crop productivity (Liu et al. 2017, He et al. 2018).

Protein content

Several studies have identified an optimal dose of approximately 30 kg N ha^{-1} to be used by foliar applications for providing the best increase in grain protein content (Bly, Woodard 2003, Ransom et al. 2016). In wheat, several studies have shown that foliar sprays of N increased grain protein. Optimum timing for N sprays on wheat showed that post-pollination foliar N gave the highest grain protein (Blandino, Reyneri 2009, Gholami et al. 2011). In the treatments with A2 fertilizer (A2N20 and A2N25), no positive effect on the increase in protein content was found compared to the control. According to Hřivna et al (2015), Yu et al. (2018), Tabak et al. (2020), nitrogen fertilization enhances the grain protein content, while sulfur fertilization affects grain protein composition. In the opinion of Yu et al., due to insufficient S supply, wheat is not capable of reaching its full yield potential and the use of N for protein synthesis may be reduced. The lower grain protein content found for the treatments with A2 fertilizer may be associated with a 17% higher grain yield, which resulted in a dilution effect and a lower protein accumulation in the grain. In our study, the nitrogen rates in the amounts of 144 and 135 kg N ha^{-1} in the variants (A2N20 and A2N25) were sufficient to obtain the maximum yields but did not ensure a protein content of 12%. Similar results in experiments with reduced nitrogen doses have been found by various other researchers (Blandino et al. 2015, Rossmann et al. 2019).

The results showed that the preceding crop had no significant impact on the protein content in winter triticale grains. This finding agrees with the reports by other researchers, who found that the choice of the preceding crop had no significant influence on the protein content of wheat grain (Jankowski et al 2015).

High grain N generally derives from re-translocation from leaves rather than new uptake. The most recent studies agree in assigning foliar fertilization timing an essential role, as late-season supply, between booting and heading, is more efficient in increasing the protein content (Brown, Petrie 2006, Fernández, Eichert 2009).

Nitrogen and sulfur uptake

One of the critical aspects in the assessment of the yield-producing efficiency of nitrogen is the effect of fertilization on the total uptake of both nitrogen and sulfur. Irrespective of the treatment applied, a significant rise in N uptake was found in comparison with the control. However, diverse nitrogen doses did not affect the total sulfur uptake, which was on average 22 kg S ha^{-1}. On the other hand, the type of nitrogen fertilizer used in the second and third doses led to varying levels of N and S accumulation in triticale grain, which is expressed by the accumulation indices for these elements. In the literature, the share of nitrogen and sulfur accumulated in the grain relative to the accumulation of these elements in the total aboveground biomass is defined as the NHI – nitrogen harvest index and SHI – sulfur harvest index (Fageria 2014).

The values of NHI in our study ranged from 72.9 to 78.26% and varied significantly depending on the level of mineral nitrogen fertilization. Compared to the control, a significant reduction in grain N accretion was found on most of the examined sites and represented the following order: AN >A2N25>A2N20>A1N20>A1N25. A similar relationship was shown by Van Hecke et al. (2020), who obtained higher NHI values in wheat at the level of 82, 83-85% for the N doses of 160 and 100 kg, respectively. Fageria et. at indicates that the most important practices that can improve NHI are liming acid soils, use of adequate N doses, source and timing, planting N efficient crop species or genotypes within species, and use of appropriate crop rotation (Fernández, Eichert 2009). Our results indicate that the preceding crop influenced the value of NHI Index. Higher values were obtained for variants with rape as the previous crop. This finding is in line with results of other reports indicating that NHI of wheat varied significantly depending on the preceding crop (Rahimizadeh et al. 2010, Litke et al. 2019)

The analysis of the sulfur harvest index shows that sulfur is accumulated to a lesser degree than nitrogen and its values ranged from 53 to 57.6%. Lower values of SHI compared to NHI indicate weaker remobilization of sulfur accumulated during the period of vegetative growth. The values of SHI also varied significantly depending on the type of fertilization and the highest accumulation of sulfur in the grain compared to the control was noted for the application of A2 fertilizer.

Nitrogen use efficiency (NUE)

Net agronomic efficiency indices (NAE) and apparent nitrogen recovery (ANR) were used to evaluate the nitrogen management of triticale. N utilization efficiency reflects the ability of the plant to translate the N uptake into economic yield (grains). Both the type of fertilizer used and the dose of N applied significantly affected the agronomic efficiency of the activity of N fertilizer, and the values of ANR increased with the reduction of the nitrogen dose in the fertilizer and ranged from 16.7 kg (control) to 34.7 kg A2N25 (Figure 6). Similar values of agronomic efficiency indices, especially for fertilizers enriched in sulfur and amino acids, were obtained by other authors (Velasco et al. 2012, Blandino et al. 2015).

The parameter: apparent nitrogen recovery refers to the agronomic efficiency of nitrogen application, which is defined as the amount of grain yield produced per unit of nitrogen applied to the soil. A higher ANR value indicates that a smaller amount of nitrogen is required to produce a certain amount of grain yield, while a lower agronomic efficiency value suggests that more nitrogen is being lost through various processes and not being utilized efficiently by the plant. The ANR value for wheat cultivation typically ranges from about 10 kg to 30 kg kg^{-1} N, meaning that for every kilogram of nitrogen applied, between 10 and 30 kg of grain yield can be expected (Mandić et al. 2015, Panayotova, Kostadinova 2015). However, in well-organized growth systems or on poor soils where low levels of nitrogen fertilization occur, an ANR value over 30 kg kg^{-1} N can be encountered. A lower ANR value suggests that changes in nitrogen management can increase plant productivity, indicating that a more efficient use of nitrogen could result in higher grain yields. The ANR value for wheat cultivation is influenced by a variety of factors, including the amount of nitrogen fertilization and the climatic conditions in which the crop is grown. The value of the nitrogen use efficiency oscillated within a broad range from 48% in the control to 75% in the treatments with reduced N rates, where a hybrid fertilization system was applied based on new-generation liquid nitrogen fertilizers. Other studies also contain information that an increasing nitrogen dose decreased nitrogen use efficiency (Haile et al. 2012, Fageria 2014). In our study, the factor influencing the NUE was also the preceding crop. Higher NUE was obtained when triticale was grown after rapeseed.

This result was similar to another study where it was also found that the preceding crop has a significant impact on NUE (Lecoeur et al. 1996). Higher values of the apparent nitrogen recovery index were due not only to reduced N doses but also to the method of nitrogen application and the presence of sulfur and amino acids in A2 fertilizer. Several studies showed that sulfur (S) fertilization may increase ANR, but no attempts have been made to explain whether this increase is due to greater recovery efficiency, an enhanced internal efficiency or an improvement of both efficiencies (Salvagiotti et al. 2008, Salvagiotti et al. 2009, Sharma, Bali 2017). Some researchers found that the efficiency of nitrogen, phosphorus, and potassium is reduced due to sulfur deficiency and ultimately reduced crop yield (Carciochi et al. 2020). In our study, the reason for the higher NUE noted for A2 fertilizer was the addition of amino acids. Vernieri et al. (2006) demonstrated that the application of protein hydrolysate influenced nitrogen metabolism in plants, speeding up the incorporation of nitrate into proteins through the activation of N assimilation-related enzymes. The increased use efficiency of nitrogen was justified by the higher leaf chlorophyll content in treated plants.

Foliar N fertilization sustains high N absorption and the use efficiency by winter triticale. Other researchers, such as Fernandez et al. and Ferrari et al. 2022, have also found that the method of nitrogen application affects the increase in nitrogen utilization (Ottman et al. 2000, Fernández et al. 2013). Much research has been conducted during the past decades to improve nitrogen use efficiency by developing fertilizer management strategies based on better synchronization between the supply and requirement of N by the crop. A recent review of worldwide data on nitrogen use efficiency (NUE) for cereal crops from researcher-managed experimental plots reported that single-year fertilizer N recovery efficiencies averaged 65% for corn, 57% for wheat, and 46% for rice (Ladha et al. 2005, Lee et al. 2020). Lower NUE could mainly be associated with N losses and methods of N application (Dhillon et al. 2019). Numerous studies have also shown that the interaction between nitrogen and other elements affects both yield and nitrogen use (Fernández et al. 2013, Carciochi et al. 2020). Fernandez et al. and Ladha et al. reported that much research has been conducted during the past decades to improve N-use efficiency by developing fertilizer management strategies based on better synchronization between the supply and requirement of N by the crop (Ladha et al. 2005, Fernández et al. 2013).

The development of crop plants with more efficient nitrogen usage is, therefore, an important research goal in achieving greater agricultural sustainability (Tiong et al. 2021). Further improvement of NUE in crops is thus an important aim in agriculture research and our future food production capabilities (Lee et al. 2021). The NUE can be improved by diversifying N sources (e.g. organic amendments, symbiotic N2 fixation) and increasing their relative contribution to total inputs, and introducing new fertilizers into practice (Blandino et al. 2015, Carciochi et al. 2020). Further improvement of NUE in crops is thus an important aim in agricultural research and our future food production capabilities.

CONCLUSIONS

The analyzed parameters depended greatly both on the treatment and the year of the experiment. When analyzing mean values for two study years, the highest yield was recorded after the application of the new fertilizer available on the market and designed for cereals cultivation. The use of the hybrid technique of nitrogen application in triticale fertilization technology at the same time reduced N fertilizer doses by 20 and 25% and significantly enhanced the yield of grain. Sulfur supplementation and amino acid compounds with the new A2 fertilizer also significantly increased the average nitrogen use efficiency from fertilizers in the range of 45% to 75%. The preceding crop affects winter triticale grain yield; however, higher results were observed when triticale was grown after rape compared to winter wheat. Considering the average protein content from four experiments, the reduction in nitrogen doses, irrespective of the liquid fertilizer used, resulted in a decline in the grain protein content compared to the control.

Exploring the possibilities of increasing plant production and efficient use of N (NUE) fertilizers without posing environmental threats is an important research area. In addition, a diagnosis of the soil fertility status is important for the development of application techniques of both nitrogen and nutrients, supporting its use efficiency. Managing fertilizer application in the field is one of the greatest challenges since it focuses on maximum efficient utilization of fertilizers to enhance crop yield and ensure environmental safety A significant increase in NUE requires the implementation of new diagnostic tools, capable of quantifying a crop plant requirement for N in real-time (a defined stage of plant development) and taking into account spatial differences on a national scale as well as the productivity of field units.

AUTHOR CONTRIBUTIONS

R.G. – methodology, R.G. – formal analysis, D.G. – investigation, R.G, J.B. – resources, R.G, J.B. – writing, original draft preparation, R.G., M.S. – writing, review and editing, R.G., R.K., K.W., M.S. – supervision, R.G., M.S. – funding acquisition, R.G., K.W. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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