Eurasian Journal of Soil Science 2025, 14(3), 253 - 261

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org

Agronomic efficiency of fertilization in triticale cultivation

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Article Info
Received : 05.02.2025
Accepted : 25.04.2025
Available online: 01.05.2025

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Abstract

The present study aims to investigate how fertilization levels impact the partial factor productivity of nitrogen, phosphorus, and potassium in triticale. The experiment was set up in four repetitions on the experimental field of the Agricultural University of Plovdiv for three years after the predecessor sunflower. The field trial included three triticale varieties: Kolorit (standard), Trismart, and Musala grown at two fertilization levels $N_{60}P_{50}K_{20}$ and $N_{120}P_{100}K_{40}$. Fertilization levels significantly affected the partial productivity values of nitrogen, phosphorus, and potassium, either separately or in total, regarding the productivity of grain and grain protein in the three triticale varieties. The average partial productivity of nutrients over the study period decreased as the level of fertilization increased. For each unit of nutrients applied, less grain or grain protein was produced at higher fertilizer rate compared to a lower one. Specifically, the results from the double fertilization rate of $N_{120}P_{100}K_{40}$ showed that the efficiency of each kilogram of nutrient imported was lower. The average partial productivity of applied PFP-NPK nutrients was higher at the low $N_{60}P_{50}K_{20}$ fertilization level. The climatic conditions during the triticale vegetation had a significant effect on the partial productivity of nitrogen, phosphorus, and potassium for grain yield. The lowest values of the partial productivity were found in the variety Trismart grown at $N_{120}P_{100}K_{40}$ level in the unfavourable climatic 2017. The productivity of all three elements was highest in the variety Musala, fertilized with $N_{60}P_{50}K_{20}$ in 2019. Unfavourable conditions in 2017 reduced the partial productivity of nitrogen for grain by 40.0 kg kg^{-1} at the level of $N_{60}P_{50}K_{20}$ and by 15.6 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Drought resulted in lower grain production per unit of phosphorus and potassium applied.

Keywords: Agronomic efficiency, fertilization, partial productivity, triticale.

Introduction

As food insecurity increases, enhancing the efficient use of water and nutrients has become a critical area of research (Fixen et al., 2015). The efficiency of farming systems is calculated as the ratio of revenues to system inputs and can be determined in different ways depending on the specific interest (Norton et al., 2015). The most used indices directly related to the use of fertilizer elements are four: partial productivity of the PFP element, agronomic efficiency AE, partial nutrient balance PNB, and recovery efficiency RE (Fixen, 2015). Two of the indices—partial productivity and agronomic efficiency—determine productive efficiency, where revenues are the primary output. The other two indices—partial nutrient balance and recovery efficiency—characterize return efficiency, reflecting how effectively plants utilize applied nutrient elements from fertilizers. The partial productivity of nutrients (PFP) resulting from fertilization evaluates the productivity of a system concerning the nutrients added. This index provides a simple way to measure yield efficiency and is calculated by dividing the crop yield by the amount of applied nutrients. The most important aspect for farmers is the ability to integrate the efficiency of elements from both the soil and applied fertilizers. It serves as a long-term trend indicator (Fixen et al., 2015). Two important conclusions

: https://doi.org/10.18393/ejss.1688572
: https://ejss.fesss.org/10.18393/ejss.1688572
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

have been drawn when studying and analyzing the effectiveness of nutrients worldwide. The efficiency of fertilization observed in research trials is greater than what is achieved in real farm conditions. Additionally, the existing data on current fertilizer usage is inadequate for various crops, farming systems, and regions. While many technologies have been developed to enhance the efficiency of fertilizers, their adoption by farmers remains significantly low (Murrell, 2011). In recent years, nutrient application on arable land has improved crop yields and increased societal understanding of nutrient efficiency (Salim and Raza, 2019). Especially in unfertile soils the crop production systems depend on nutrient supply (Salim and Raza, 2019). Moreover, precise agriculture management practices enable the application of nutrients at the proper time and rate (Salim and Raza, 2019).

In 2023, according to FAO, production areas with triticale amounted to almost 4 million ha. (FAOSTAT, 2023). The main reason for the great popularity of triticale is the high and stable productivity in a poor nutritional regime, as well as the resistance to diseases, enemies, and adverse environmental factors (Feledyn-Szewczyk et al., 2020, Jańczak-Pieniążek, 2023). Crop productivity is influenced by various factors. These include advancements in cropping systems, the application of production inputs such as high levels of nitrogen fertilization, and effective crop protection methods. Additionally, the distribution of precipitation throughout the growing season and the efficiency of nitrogen use play crucial roles in determining crop yields (Taiz, 2013, Iizumi and Ramankutty, 2015, Sirakov et al., 2021). Fertilizer application aims to bring the yield closer to the standard values and even exceed them (Gaj et al., 2023). In most cases, the amount of fertilizers introduced to obtain the planned yield is greater than the actual quantity of nutrients that the culture needs (Gaj et al., 2023). Plant assimilation, substrate absorption, ammonia volatilization, and denitrifications are among the possible ways to remove excess nitrogen from the soil (Wang and Xing, 2016). Sustainable fertilization practices require a combined approach to increase productivity while respecting soil health and protecting the environment (Erisman et al. 2018).

This study aims to determine the effect of fertilization level on the partial factor productivity of nitrogen, phosphorus, and potassium on triticale.

Material and Methods

Experimental setup

The experiment was performed at the experimental field of the Agricultural University of Plovdiv, Bulgaria (42°9' N, 24°45'' E, 160 m altitude) during the period 2016-2019 under non-irrigated conditions. The field trial included triticale varieties Kolorit (standard), Musala, and Trismart, created in different breeding centers and grown at two fertilization levels: $N_{60}P_{50}K_{20}$ and $N_{120}P_{100}K_{40}$. The experiment was set according to the block method in 4 repetitions with a test area of 15 m^2 after the predecessor sunflower. The fertilization with the triple superphosphate (46% P_2O_5) and potassium chloride KCl (60% K_2O) took place pre-sowing before the first soil cultivation, and nitrogen in the form of ammonium nitrate NH_4NO_3 (34% N) was applied once in early spring. Sowing was carried out within the appropriate agrotechnical period (depending on the conditions in the autumn and a sowing rate of 550 germinated seeds/m^2). Weed control was consistent with the level of weeding conducted in the respective spring. The herbicide Acurat 60 WG (Metasulfuron-methyl) was applied at a dose of 10 g ha^{-1} to target annual and perennial broadleaf weeds during the tillering phase.

At maturity, the total nitrogen concentration of triticale grain was determined using the Kjeldahl method, following wet digestion with H_2SO_4 and H_2O_2 as catalysts (Tomov et al., 2009). The grain protein concentration was calculated from the grain nitrogen percentage multiplied by a coefficient of 5.6 (Mariotti et al., 2008). The grain protein yield, measured in kilograms per hectare (kg ha^{-1}), was calculated using the following formula: (Grain yield in kg.ha^{-1} multiplied by the percentage of protein in the grain) / 100.

The partial productivity of applied nutrients (N, P_2O_5, K_2O, or total NPK) was calculated based on grain yield and triticale grain protein yield. This was expressed as the ratio of grain yield (or grain protein yield) to the amounts of nitrogen, phosphorus, and potassium applied through fertilizers, as described by Dobermann (2007).

Partial factor productivity (PFP), kg kg^{-1} = Grain or Protein yield in kg ha^{-1} / Fertilizer rate of N, P_2O_5, K_2O, NPK in kg ha^{-1}.

Soil characterization

The experiment was conducted on alluvial-meadow soil *Mollic fluvisols*, the weakly solonetz, with a power of horizon A 25 – 28 cm (Popova et al., 2012). The soil is medium sandy loam with a physical clay content in the A horizon of 33%. The soil contains a moderate amount of calcium carbonate, which gives it better physico-chemical and aquatic properties. The reaction of the soil is slightly alkaline with an average value of 7.80 in the 0-30 cm layer and 7.70 in the 30-60 cm layer (Popova et al., 2012). The cation sorption capacity and the degree of base saturation are relatively high (20-30 mequ/100g and 90-92%, respectively). The content of organic matter is 1.3% (Popova et al., 2012). The content of mineral nitrogen and available phosphorus and potassium in the soil before sowing of the triticale was determined in soil layers 0-30 and 30-60 cm (Table 1). The results show that the soil was poorly stocked with mineral nitrogen, well stocked with mobile phosphorus, and very well stocked with absorbable potassium.

Table 1. Content of mineral nitrogen and mobile forms phosphorus and potassium before sowing triticale.

Year	0-30 cm			30-60 cm		
	Nmin, mg kg^{-1}	P_2O_5, mg/100 g	K_2O, mg/100 g	Nmin, mg kg^{-1}	P_2O_5, mg/100 g	K_2O, mg/100 g
2016	25.9	25.8	41,3	20.7	19.9	34.0
2017	30.2	27.3	43.2	23.5	21.1	32.6
2018	24.7	26.9	51.1	19.3	22.8	34.4

Weather conditions

The study was conducted in an experimental field located in the transitional Mediterranean climatic sub-region of the European-continental region of Bulgaria. This agroclimatic region is characterized by warm springs and autumns, which are relatively short. The average annual temperature does not fall below 13 °C, and the annual temperature amplitude does not exceed 23^0 C. The highest rainfall occurs in early summer, during May and June, while a minimum of precipitation is recorded in early autumn, in August and September (Peev and Kouzmova, 2002). The hydrothermal conditions during the three vegetation periods of the triticale are presented in Figure 1. Their analysis points out that the first experimental year differs from the average multiannual average. The autumn drought delayed the germination phase, and the air temperature was close to the minimum temperatures for the growth and development of triticale. January was characterized as cold, and the average monthly temperature (-3.9°C) was lower than the climate average. Typical for this month were the sharp and short-term decreases in temperatures to - 10.3°C and the lack of snow cover, which posed a real threat to the crop, but despite the low temperatures, no frost has been recorded. The total amount of rainfall during the vegetation of the triticale is 271.6 mm below the climate average of the region. The second experimental year was characterized by a sum of the average monthly temperatures exceeding the climate average by 2.1 °C. A sufficient amount of precipitation contributed to a better moisture supply of the soil and the optimal development of the triticale. Hydrothermal conditions in the third year were similar to the second year, with positive temperatures in the autumn-winter period exceeding the multiannual period.

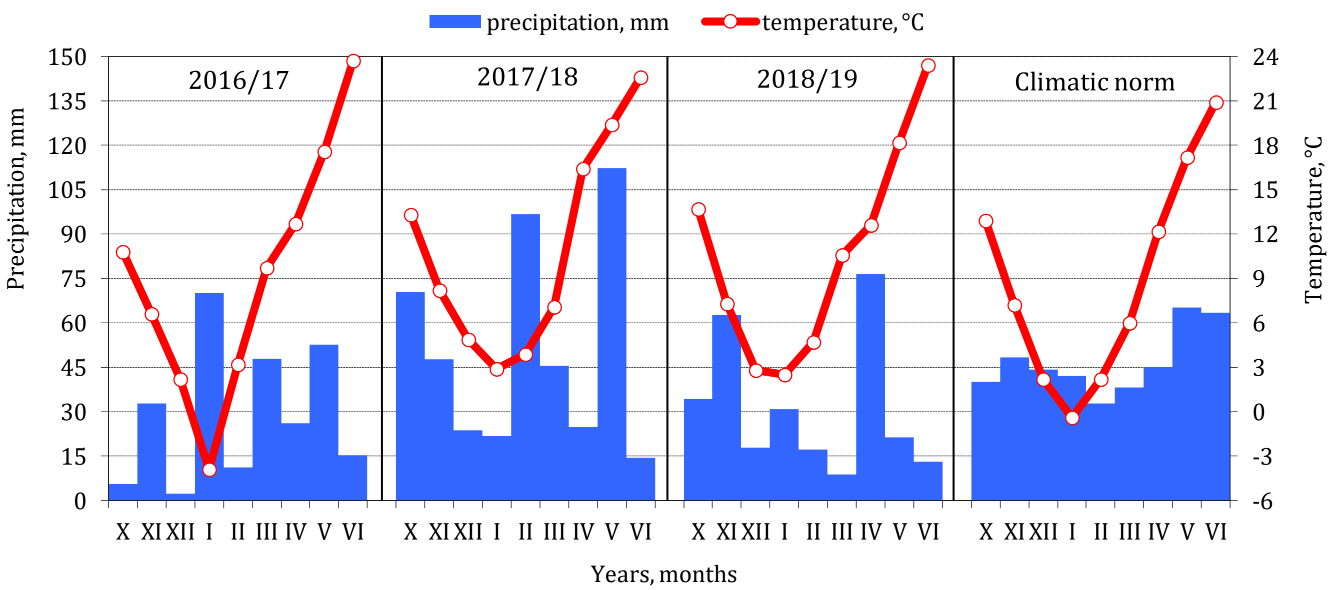

Figure 1. Climatogram during triticale vegetation.

Data Analysis

For statistical data processing one way ANOVA and Duncan's multiple range test (P = 0.05) were used to find significant differences among means. The Pearson correlation coefficient was determined with XLSTAT Version 2016.02.

Results and Discussion

The fertilization level has a proven positive effect on the yield of grain and grain protein from triticale. The result of the higher fertilization level $N_{120}P_{100}K_{40}$ is an increase in the average grain and grain protein yield of the varieties by 42.0 % and 72.1 %, respectively (Tables 2 and 3). The productivity of the three varieties varies widely, and no proven varietal differences have been found on average over the three years. The grain yield varies from 2013 kg ha^{-1} (variety Kolorit at level $N_{60}P_{50}K_{20}$ in 2017) to 6622 kg ha^{-1} (variety Musala at level $N_{120}P_{100}K_{40}$ in 2019). In terms of grain protein yield, the lowest value of 128.2 kg ha^{-1} was obtained by the variety Trismart fertilized with $N_{60}P_{50}K_{20}$ in 2017, and the highest yield of 445.5 kg ha^{-1} was obtained from the variety Musala at the level of $N_{120}P_{100}K_{40}$ in 2019. The influence of climatic conditions during the vegetation on the productivity of triticale is significant. In 2017, the grain yields were at their lowest values due to unfavourable conditions. However, in the following two years, the improved conditions resulted in a significant increase in yields, with nearly a twofold rise in 2019 compared to 2017. It is known that the yield of grain protein from triticale determines the nutritive value of the feed and the use of the crop as a raw material for the livestock industry. The influence of climatic factors has been demonstrated in the present study. At the low fertilization level $N_{60}P_{50}K_{20}$, less grain protein was obtained from triticale in 2017 than protein yields in 2018 and 2019. With increased fertilization $N_{120}P_{100}K_{40}$, significant differences were observed between the obtained grain protein yields in the 2017 and 2019 harvest years, while the protein yield in 2018 did not differ significantly from that of 2017 and 2019. Other authors have also confirmed mineral nutrition's positive effect on the triticale grain's protein content (Jaśkiewicz and Szczepanek, 2018; Hospodarenko and Liubych, 2021; Muhova et al., 2024). The same researchers reported a significant effect of the weather conditions during the growing season on the nitrogen-containing compounds in triticale grain. Those results also correspond to the findings of Lalević et al. (2019). Lestingi et al. (2010) reported that a small input of nitrogen of 50 kg ha^{-1} instead of 100 kg ha^{-1} ensured a good productivity and quality of the triticale grain. By changing the input conditions from low to optimum triticale grain performance increases by 68% (Vats et al., 2016). The same authors reported that triticale responded differently to mineral nutrition depending on the genotype. According to Knapowski et al. (2009), increased nitrogen rates between 80 and 120 kg ha-^{1} led to a 9.6% increase in triticale productivity. Janušauskaitė (2013) observed that a nitrogen rate of 90-120 kg ha^{-1} is optimal in economic terms for achieving high yields from spring triticale. Many researchers (Cimrin et al., 2004; Mut et al., 2005) confirmed the positive effect of higher nitrogen rates on triticale. According to Mut et al. (2005) triticale can use very high doses of nitrogen.

Table 2. Grain and grain protein yields of triticale depending on the fertilization level and cultivar.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization	$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$			
Grain yield, kg ha^{-1}								
Kolorit	2013	4028	4604	3548^{ns}	3925	5472	5842	5080^{ns}
Musala	2161	4803	5301	4088	4419	6223	6622	5755
Trismart	1989	3856	4105	3317	3448	5158	5556	4721
Average	2054^{a*}	4229^{b}	4670^{b}		3931^{a}	5618^{b}	6007^{b}	
Grain protein yield, kg ha^{-1}								
Kolorit	131.4	210.7	258.6	200.2^{ns}	264.1	334.1	434.1	344.1^{ns}
Musala	136.7	233.3	286.8	218.9	309.2	395.5	445.5	383.4
Trismart	128.2	191	220.4	179.9	233.6	330.6	344.3	302.8
Average	132.1^{a}	211.7^{b}	255.3^{b}		269.0^{a}	353.4^{ab}	408.0^{b}	

[*] Values within columns followed by different lowercase letters are significantly different at ($P<0.05$)

The partial productivity clarifies fertilization's efficiency and is calculated in units of crop yield per unit of nutrient applied. In this study, it was observed that varying levels of fertilization had a significant impact on the partial productivity of nitrogen, phosphorus, and potassium, both individually and in combination. This, in turn, affected the overall productivity of grain and grain protein across three different varieties of triticale. (Table 3). The average partial productivity of nutrients decreases as the level of fertilization increases. This indicates that, for each unit of nutrients applied, less grain or grain protein is produced at higher fertilizer rates compared to lower rates. The result of the double fertilization rates $N_{120}P_{100}K_{40}$ is a lower efficiency of each kilogram of fertilizer element applied. The grain formed per unit of nitrogen is less by 17.7 kg, per unit of phosphorus by 21.1 kg, and per kilogram of fertilizer potassium by 53.0 kg.

The application of nitrogen, phosphorus, and potassium fertilizers significantly impacts the partial productivity of grain protein yield (Table 3). The average partial productivity of nutrients for the grain protein yield of triticale varieties shows a trend similar to that of grain yield. The higher fertilization level lowers by an average of 14.0% the partial productivity of nitrogen, phosphorus, and potassium compared to

$N_{60}P_{50}K_{20}$ fertilization. Twofold higher rates reduced partial productivity for grain protein by 0.5 kg kg^{-1} for PFPpr-N, 0.6 kg kg^{-1} for PFPpr-P and 1.4 kg kg^{-1} for PFPpr-K. At both fertilization levels, the highest mean values for partial potassium productivity were found for grain protein yield of 9.98 ($N_{60}P_{50}K_{20}$) and 8.59 ($N_{120}P_{100}K_{40}$). The productivity of nitrogen and phosphorus to form grain protein yield from triticale is in a relatively narrow range of 2.86 – 3.99 kg kg^{-1}. The average partial productivity of applied PFP-NPK nutrients is higher at the low $N_{60}P_{50}K_{20}$ fertilization level. It is 28.1 kg kg^{-1} for grain yield and 1.54 kg kg^{-1} for grain protein yield. The increase in fertilization for triticale has been shown to reduce the partial productivity of 1 kg of NPK. The results indicate a more significant reduction of 8.2 kg kg^{-1} in partial productivity for grain yield PFPg-NPK, while partial productivity for grain protein PFPpr-NPK is reduced by 0.2 kg kg^{-1}. These results correspond with what was found by Dibb (2000) that for a given soil and growing conditions, the efficiency of nutrient utilization in most cases decreases with increasing amount of element applied.

Table 3. Effect of the fertilization level on the productivity and partial factor productivity of triticale.

Variables	$N_{60}P_{50}K_{20}$	$N_{120}P_{100}K_{40}$	Difference
Grain yield	3651	5185***	1534.0
Protein grain yield	199.7	343.4***	143.7
PFPg-N	60.9	43.2***	-17.7
PFPg-P	73.0	51.9***	-21.1
PFPg-K	182.6	129.6***	-53.0
PFPg-NPK	28.1	19.9***	-8.2
PFPpr-N	3.33	2.86***	-0.5
PFPpr-P	3.99	3.43**	-0.6
PFPpr-K	9.98	8.59**	-1.4
PFPpr-NPK	1.54	1.32**	-0.2

** significance at P<0.05, *** significance at P<0.01, PFPg-partial factor productivity for grain yield, PFPpr-partial factor productivity for protein yield

The varietal response of triticale in productivity of nitrogen, phosphorus, and potassium for grain yield on average over the three years is weak and insignificant (Table 4). However, both fertilization levels tended to make more efficient use of nutrients from soil stocks and applied fertilizers to form yield grain of variety Musala. Lower values of PFPg-N, PFPg-P and of PFPg-K are found for Trismart cultivar, while the standard Kolorit occupies an intermediate position. These data reflect the grain yields obtained from the different varieties. Growing Musala variety at an increased fertilization level $N_{120}P_{100}K_{40}$ reduces the partial productivity of nitrogen, phosphorus, and grain potassium by 20.1 kg kg^{-1}, 24.3 kg kg$^{-1,}$ and 60.5 kg kg^{-1}, respectively, compared to fertilization with $N_{60}P_{50}K_{20}$. The differences in nutrient yield performance between the two fertilization levels by the Trismart variety were 16.0 kg kg^{-1} for PFPg-N, 19.1 kg kg^{-1} for PFPg-P, and 47.8 kg kg^{-1} for PFPg-K. The values of the partial productivity of the nutrients for grain yield from the triticale vary widely: 28.7-88.4 kg kg^{-1} for PFPg-N, 34.5-106.0 kg kg^{-1} for PFPg-P, 86.2-265.1 kg kg^{-1} for PFPg-K. Within the framework of this study, the lowest values for the partial productivity of nitrogen, phosphorus, and potassium were found in the variety Trismart grown at $N_{120}P_{100}K_{40}$ level in the climatically unfavourable 2017. The productivity of all three elements is highest in the variety Musala, fertilized with $N_{60}P_{50}K_{20}$ in 2019.

Table 4. Partial factor productivity of nitrogen, phosphorus, and potassium for grain yield of triticale depending on the fertilization level and cultivar, kg kg^{-1}.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization	$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$			
PFPgrain-N								
Kolorit	33.6	67.1	76.7	59.1 ^{ns}	32.7	45.6	48.7	42.3 ^{ns}
Musala	36.0	80.1	88.4	68.1	36.8	51.9	55.2	48.0
Trismart	33.2	64.3	68.4	55.3	28.7	43.0	46.3	39.3
Average	34.2 ^{a*}	70.5 ^{b}	77.8 ^{b}		32.8 ^{a}	46.8 ^{b}	50.1 ^{b}	
PFPgrain-P								
Kolorit	40.3	80.6	92.1	71.0 ^{ns}	39.3	54.7	58.4	50.8 ^{ns}
Musala	43.2	96.1	106.0	81.8	44.2	62.2	66.2	57.5
Trismart	39.8	77.1	82.1	66.3	34.5	51.6	55.6	47.2
Average	41.1 ^{a}	84.6 ^{b}	93.4 ^{b}		39.3 ^{a}	56.2 ^{b}	60.1 ^{b}	
PFPgrain-K								
Kolorit	100.7	201.4	230.2	177.4 ^{ns}	98.1	136.8	146.1	127.0 ^{ns}
Musala	108.1	240.2	265.1	204.4	110.5	155.6	165.6	143.9
Trismart	99.5	192.8	205.3	165.8	86.2	129.0	138.9	118.0
Average	102.7 ^{a}	211.5 ^{b}	233.5 ^{b}		98.3 ^{a}	140.4 b	150.2 ^{b}	

* Values within columns followed by different lowercase letters are significantly different at (P<0.05)

The climatic conditions during the triticale vegetation have a significant effect on the partial productivity of nitrogen, phosphorus, and potassium for grain yield (Table 4). In the climate-friendly 2018 and 2019 years, the partial nitrogen productivity for grain yield is on average 74.2 kg kg^{-1} when fertilized with $N_{60}P_{50}K_{20}$ and an average of 48.5 kg kg^{-1} at the $N_{120}P_{100}K_{40}$ level. In the same years, the partial productivity of phosphorus is in the range of 84.6-93.4 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 56.2-60.1 kg kg^{-1} ($N_{120}P_{100}K_{40}$). The partial productivity of potassium for grain yield is more than twice as high as that of nitrogen and phosphorus, with favourable hydro-thermal conditions for triticale averaging 119.4 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 145.3 kg kg^{-1} ($N_{120}P_{100}K_{40}$). Lower average values for the three varieties were obtained in the dry year 2017 compared to those of 2018 and 2019. This is found at both fertilization levels. Unfavourable hydro-thermal conditions in 2017 reduced the partial productivity of nitrogen for grain by 40.0 kg kg^{-1} at the level of $N_{60}P_{50}K_{20}$ and by 15.6 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Drought led to the formation of less grain per unit of phosphorus applied, with a reduction of 47.9 kg kg^{-1} at the $N_{60}P_{50}K_{20}$ level and 18.8 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Decreases of 119.8 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 47.0 kg kg^{-1} ($N_{120}P_{100}K_{40}$) were found in the partial productivity of grain potassium. The varietal response of triticale is unproven in terms of the partial productivity of nitrogen, phosphorus, and potassium for grain protein yield on average over the three years (Table 5). This is demonstrated at both fertilization levels. According to Alaru et al (2003), the main factor that affects the protein content and the grain yield is the variety, not the nitrogen fertilization. The results obtained were unidirectional, with the observed trend by the three cultivars for partial productivity of the grain yield nutrient. The highest partial productivity for grain protein yield of 4.78 kg kg^{-1} for applied nitrogen, 5.74 kg kg^{-1} for applied phosphorus, and 14.34 kg kg-1 for applied potassium was observed in the variety Musala fertilizer with $N_{60}P_{50}K_{20}$ in 2019. The values of these indicators are lowest in the variety Trismart grown at an increased fertilization level $N_{120}P_{100}K_{40}$ during the climatic unfavourable 2017 and are 1.95 kg kg^{-1} for PFPpr-N, 2.34 kg kg^{-1} for PFPpr-P and 5.84 kg kg^{-1} for PFPpr-K. The less favorable conditions in 2017 led to lower values of the partial productivity of nitrogen, phosphorus, and potassium compared to the other two experimental years. Quantitatively the difference is more significant at the low fertilization level $N_{60}P_{50}K_{20}$. In the same year, the resulting grain protein on average for the varieties was less by 1.33–2.05 kg per kilogram of nitrogen applied, 1.59-2.47 kg per kilogram of phosphorus fertilizer, and 3.97-6.15 kg per kilogram of potassium fertilizer. A proven effect of the year factor on the partial productivity of nitrogen, phosphorus, and potassium for grain protein yield when fertilizing triticale with $N_{120}P_{100}K_{40}$ was found between the average annual values of 2017 and 2019. More favorable hydro-thermal conditions in 2019 led to an average increase of 51% in partial productivity of the elements. Gülmezoğlu and Kutlu (2017) observed that increased N rates stimulate the grain protein and the total N uptake, as the highest protein content was recorded when applying 160 kg ha^{-1}. The same authors reported that the increased N rates decrease all nitrogen use efficiency indexes. Moreover, those indices differed according to the triticale genotype, and the agronomic efficiency was highest at a 40 kg ha^{-1} application rate, when each kg of applied nitrogen produced 8.8 kg kg $^{-1}$ grain. Sobkowicz and Śniady (2004) determined that triticale realized the highest yields at 23 kg per kg N. The agronomic efficiency could be affected by abiotic factors, as well as the genotype, but in general, the parameter decreases while increasing levels of N (Sobkowicz and Śniady, 2004; Aynehband et al., 2012; Janušauskaitė, 2013).

Table 5. Partial factor productivity of nitrogen, phosphorus, and potassium for protein yield of triticale depending on the fertilization level and cultivar, kg kg^{-1}.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization	$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$			
PFPpr-N								
Kolorit	2.19	3.51	4.31	3.34 ns	2.20	2.78	3.62	2.87 ns
Musala	2.28	3.89	4.78	3.65	2.58	3.30	3.71	3.20
Trismart	2.14	3.18	3.67	3.00	1.95	2.76	2.87	2.52
Average	2.20 a*	3.53 b	4.25 b		2.24 a	2.95 ab	3.40 b	
PFPpr-P								
Kolorit	2.63	4.21	5.17	4.00 ns	2.64	3.34	4.34	3.44 ns
Musala	2.73	4.67	5.74	4.38	3.09	3.96	4.46	3.83
Trismart	2.56	3.82	4.41	3.60	2.34	3.31	3.44	3.03
Average	2.64 a	4.23 b	5.11 b		2.69 a	3.53 ab	4.08 b	
PFPpr-K								
Kolorit	6.57	10.54	12.93	10.01 ns	6.60	8.35	10.85	8.60 ns
Musala	6.84	11.67	14.34	10.95	7.73	9.89	11.14	9.59
Trismart	6.41	9.55	11.02	8.99	5.84	8.27	8.61	7.57
Average	6.61 a	10.58 b	12.76 b		6.72 a	8.84 ab	10.20 b	

* Values within columns followed by different lowercase letters are significantly different at (P<0.05)

A strong correlation has been observed between the grain yield and the grain protein yield (0.936) and between their partial factors' productivity (0.941) (Table 6). The relationship between the yield and the partial factors productivity of the protein is moderately dependent (0.584). The scatterplots illustrate the determined relations (Figure 2) and define the strong positive relation between the yield and the protein as roughly linear. Wojtkowiak et al. (2015) also reported a linear dependence between the protein content and the grain yield. In their findings, the protein yield increased with an increase in the grain yields, as the coefficient of determination was close to the linear correlation coefficient.

Table 6. Correlation matrix (Pearson).

Variables	Yield	Protein	PFP-Y	PFP-P
Yield	1			
Protein	0.936	1		
PFP-Y	0.397	0.098	1	
PFP-P	0.584	0.361	0.941	1

*Values in bold are different from 0 with a significance level alpha=0,05

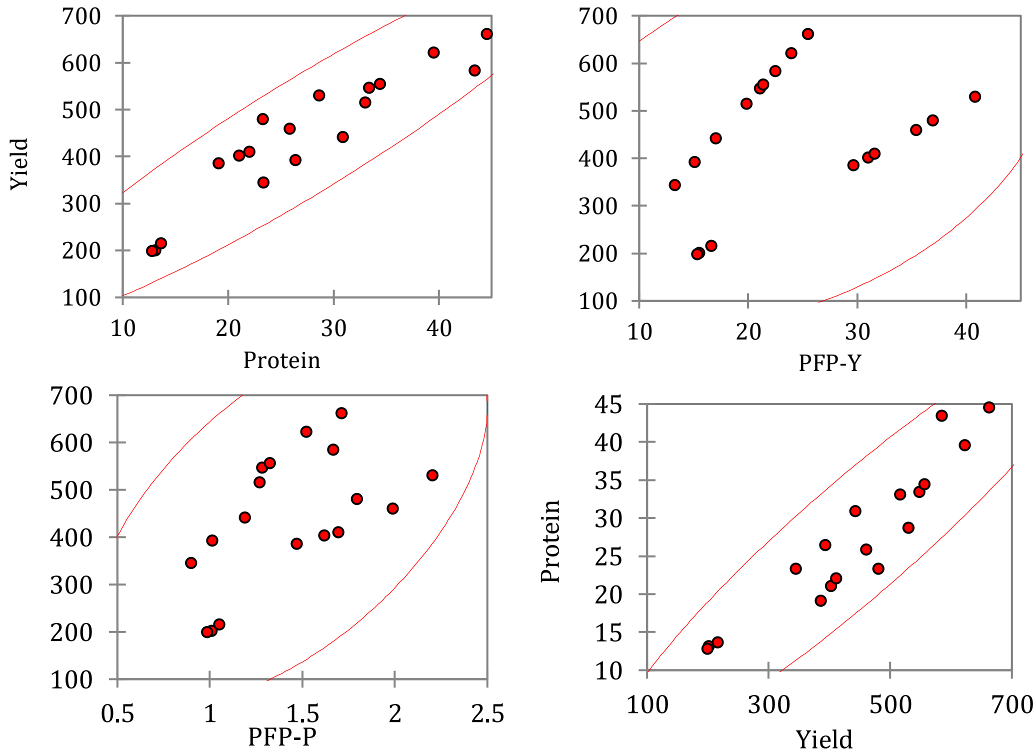

Figure 2. Correlation scatter plots between Yield, protein and PFP.

Conclusion

Higher levels of fertilization significantly increased not only the overall yield but also the yield of crude protein in the three varieties of triticale. Throughout the testing period, productivity varied greatly due to mineral nutrition and yearly conditions, while the differences among the varieties were not significant. Fertilization level had a significant impact on the partial productivity of nitrogen, phosphorus, and potassium. The average partial productivity of nutrients decreases as the level of fertilization increases. For each unit of nutrients applied, less grain or grain protein is produced at higher fertilizer rates compared to lower rates. The result of the double fertilization rates $N_{120}P_{100}K_{40}$ is a lower efficiency of each kilogram of fertilizer element applied. The varietal response of triticale in the productivity of nitrogen, phosphorus, and potassium for grain yield is weak and insignificant. However, both fertilization levels tended to make more efficient use of nutrients from soil stocks and applied fertilizers to form the grain yield of the variety Musala.

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