Original scientific paper

Efficiency of wheat mineral nutrition depending on year conditions and fertilization intensity

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Abstract
Research on efficiency of mineral nutrition of winter wheat in four production years (2008/09 - 2011/12) were carried out on stationary field trial of the Institute of Field and Vegetable Crops at Rimski Šančevi. In the paper are presented the average wheat yields in 20 fertilization variants with increasing rates of nitrogen, phosphorus and potassium and agronomical use efficiency of the applied fertilizers was calculated.

Nitrogen had significantly highest impact on the wheat yield. The highest increase in the yield with one kilogram of the used fertilizer was with nitrogen (in four years average 36.19 kg of the grain/1 kg of N used); followed by phosphorus (12.65 kg of the grain/1 kg P_2O_5), and the lowest was with potassium (4.95 kg grain/1 kg K_2O). Agronomical nitrogen use efficiency differed depending upon weather conditions of the year, but in all analyzed years as well as in the average it had tendency to decrease with increasing intensity of fertilization. The highest efficiency of the applied nitrogen fertilizers was achieved with fertilization by 50 kg N ha^{-1}. However, from the aspect of joint impact on the yield of wheat grain, use efficiency and eventual loss of nitrogen and environment pollution, variant with application of the medium nitrogen rate of 100 kg N ha^{-1} proved to be especially rational.

Key words: wheat, yield, fertilization, nitrogen, nutrient efficiency.

Introduction
In several last decades in Serbia huge experimental material on mineral nutrition and fertilization of wheat was collected. However, having in mind dominant influence of mineral nutrition in synthesis of primary production of organic matter and yield formation, this problem, although it has been intensively studied, will remain in the focus of interests of scientists and practitioners until a man keeps growing plants (Sarić and Jocić, 1993). Strong incentive to the studies of different problems of mineral nutrition of wheat provides also constant improvement in selection and creation of new varieties. Thus, with the appearance of new wheat varieties (significantly different in number of useful traits, especially by significantly higher yield potential), it turns out that their requirements in regard to mineral nutrition are much higher (Sarić and Kovačević, 1981).

Up to now obtained results of trials carried out in Serbia suggest that winter wheat during vegetation uses relatively high amounts of mineral elements and that it has high demands according to soil fertility (Malešević, 2008). Concerning macro elements that it uptakes from the soil, wheat the most absorbs nitrogen, less potassium, significantly less phosphorus and much less sulphur, magnesium and calcium (Čurić, 1982). Amounts of nutritive elements that wheat absorbs from the soil during vegetation predominantly depend on grain yield and mass of the vegetative organs. In our conditions, the most frequently applied nitrogen rates for achievement of high yields in total values are from 80-120 kg ha^{-1} depending upon agrochemical properties of the soil. Based upon results of several years lasting studies, Kastori et al. (1991) stated that for the yield of 5 t of wheat grain and adequate straw mass wheat from the soil adopt about 120 kg N, 90 kg P_2O_5 and 80 kg K_2O.

Among elements of mineral nutrition, nitrogen has the greatest role in increase of wheat yield (Bogdanović, 1985; Malešević et al., 1994; Malešević, 2008; Kastori et al., 2005). Nitrogen shows the highest efficiency when it used together with phosphorous and potassium, while these two elements used without nitrogen do not provide a significant increase in wheat yield, but they even often reduce it (Sarić et al., 1973, 1993). Deficiency of nutrition, as well as too large fertilizer rates can cause reduction in wheat yield (Čurić, 1982; Kastori et al., 1991, 2005). Use of higher amounts of fertilizers than needed proved not only economically inappropriate results from the point of view of direct investments, but for higher number of plant species and varieties such rates can be also harmful (lodging and more intensive occurrence of wheat diseases, etc.), and are frequent cause of agro ecosystem pollution.

Efficient fertilization with nitrogen is of the key element for economically production of wheat, but also for protection of underground and above ground waters from pollution caused by leaching of nitrates due to excessive and inappropriate application of N (Vuković et al., 2008). Efficiency of nitrogen application in winter wheat is valuable indicator of rational N-fertilization. The term "Nitrogen Use Efficiency" *(NUE)* has several definitions and execution procedures, depending on the purpose of the study (Dobermann, 2005; Xie et al., 2007). In agricultural practice the most wide spread is use of *Agronomic N use Efficiency* (AE_N), based on the "method of difference" and it is determined as the ratio of the yield increase achieved by N-fertilization and the used amounts of N (Craswell and Godwin, 1984; Raun and Gordon, 1999; Dobermann, 2005):

$$AE_N = \Delta GY / F_N \textit{ (kg grain / 1 kg N)}$$

where ΔGY = grain yield on the plot fertilized by nitrogen – grain yield on control plot (without N use); F_N – amount of used N in fertilized variant.

Dobermann (2005) states that typical values of AE_N in wheat are between 10–30 kg of grains per 1 kg of the applied N, and values >30 kg kg^{-1} are met in well organized growing systems or at low levels of nitrogen fertilization and on poor soils. Raun and Gordon (1999) stated that on the global level, worldwide NUE in cereal production is 33%.

Nitrogen use efficiency from mineral fertilizers in winter wheat is reduced with the increase in N fertilization level (Sieling et al., 1998). Hatfield and Prueger (2004) found that NUE depends also on water inflow (precipitations) and the availability of N to the plants during growing season. Use of nutrients from fertilizers and forming of wheat yield are significantly influenced by weather conditions during the year and specific conditions of the site (Bertić et al., 2007).

Material and Methods

Research on winter wheat (WW) mineral nutrition efficiency was conducted on a long-term stationary field trial, established in 1965/66 on experimental fields of the Institute of Field and Vegetable Crops at Rimski Šančevi. The trial is based on 4-year crop rotation (four fields) including sugar beet, maize, sunflower and wheat, as the most typical field crops in Vojvodina Province. In this paper results from last four years of experiment (from 2008/09 - 2011/12) were presented.

The trial was set up on a calcareous chernozem soil type, with slightly alkaline reaction (pH in H_2O=7.64), moderate content of humus (3.27%) and readily available phosphorus (15.98 mg/100 g of soil) and with high content of readily available potassium (25.64 mg/100 g of soil).

The experiment was set up in 4 separate fields, where different crops were grown on different fields each year. The size of each field is 1,84 ha (68 x 270 m) and is divided into 4 replication with 20 experimental plots in every replication, meaning that every field is divided into 80 plots with randomized treatments (different NPK doses and ratios), where every plot is additionally divided into more subplots, depending on the number of varieties examined.

The purpose of stationed plots in this trial was to investigate the effects of different nitrogen, phosphorus and potassium doses and ratios on wheat yield and grain quality in a continuous cropping. Considering this, founders of the trial have determined 20 different combinations of amounts and ratios of N, P_2O_5 and K_2O, according to agro-ecological conditions and biological properties of the investigated species. Fertilization treatments were:

1. Control (unfertilized plot)	11. $N_2P_1K_1$
2. N_2	12. $N_2P_2K_1$
3. P_2	13. $N_2P_2K_2$
4. K_2	14. $N_2P_3K_1$
5. N_2P_2	15. $N_2P_3K_3$
6. N_2K_2	16. $N_3P_1K_1$
7. P_2K_2	17. $N_3P_2K_1$
8. $N_1P_1K_1$	18. $N_3P_2K_2$
9. $N_1P_2K_1$	19. $N_3P_3K_2$
10. $N_1P_2K_2$	20. $N_3P_3K_3$

where index number represents doses of pure active matter of each nutrient: $_1$=50, $_2$=100, $_3$=150 kg of N, P_2O_5 and K_2O per ha.

For investigation purpose, winter wheat variety NS-40S was chosen, as one of the most widespread in Vojvodina region. It is middle late variety, with good low-temperature resistance and excellent resistance to lodging. The 1000 grains weight is in range 36-42 g and hectolitre mass is about 76-82 kg. Each year standard cultivation practice for agro-ecological conditions in Vojvodina is applied. The whole amount of P_2O_5 and K_2O and the half of the N dose were applied in autumn before tillage. Remaining amount of N fertilizers for wheat was given in spring at topdressing and before seeding for other species in the trial. Wheat straw and harvest residues of other crops are ploughed under after harvest. In all four years of investigation, sowing was done in optimal sowing time for conditions of Vojvodina (in October) with sowing density of 500 viable seeds per m^2, and spacing between rows of 12.5 cm. Application of pesticides was done sporadically, only if it was necessary.

Weather conditions in analyzed years (Table 1) indicate that the year 2008/09 was moderately hotter in relation to Long-Term Average values (LTA for period 1964-2012), mostly due to higher temperatures during winter months as well as in critical periods for wheat growth – April and May. The total amount of precipitation during this production year was similar to LTA value (-29 mm), but the severe drought in April (only 4 mm of rain), might possibly had a negative effects on grain yield. In contrary in 2009/10 year temperature conditions were more favourable with minor monthly deviations, whereby amount of precipitation were significantly higher in all months of WW vegetation period. Total rainfall amount in WW vegetation season in this year was 773 mm, i.e. 321 mm more in comparison to LTA value.

Weather conditions in 2010/11 and 2011/12 indicates that both years were moderately dry, due to low precipitation amounts in March, i.e. at the beginning of spring vegetation, and also in June, during the period of grain filling and ripening. In comparison to LTA, in 2010/11 growing season there was only 389 mm of rainfall, i.e. for 63 mm less than LTA (452 mm). In 2011/12 during WW growing season in relation to LTA, precipitations were for 88 mm lower. However, in 2011, winter reserves of moisture in the period October-March were somewhat more favourable, i.e. 266 mm in comparison to 2012 with only 200 mm (58 mm less in comparison to the LTA). Average temperature conditions in these years were on the LTA level, with higher deviations in November and December, which couldn't have negative effects on WW. However, temperature conditions in April, period of intensive growth (stem elongation), were somewhat higher (about 2ºC), and in addition with dry April in 2011, could significantly decreased WW yield in this year.

Table 1. Precipitation and temperature conditions at Rimski Šančevi experimental station (N 45° 19`, E 19° 50`) during WW vegetation period (X-VI)

Year		Month									WW veget. period (X-VI)	Difference to LTA
		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.		
T (°C)	2008/09	13.2	7.9	3.7	-1.5	2.2	6.8	14.6	18.6	19.6	9.5	1.1
	2009/10	11.7	8.3	3.5	-0.6	1.9	6.8	12.3	17.0	20.2	9.0	0.7
	2010/11	9.1	9.5	0.8	0.1	-0.2	6.0	13.2	16.8	20.9	8.5	0.1
	2011/12	10.7	2.8	4.2	2.0	-5.0	8.0	13.0	17.2	22.5	8.4	0.0
	LTA[1]	11.5	6.1	1.4	-0.4	1.5	6.3	11.4	16.9	20.0	8.3	-
P (mm)	2008/09	18	58	43	41	47	35	4	50	127	423	-29
	2009/10	82	63	97	76	66	39	64	114	172	773	+321
	2010/11	67	47	64	25	37	26	23	63	37	389	-63
	2011/12	35	2	49	43	67	4	83	51	31	365	-88
	LTA[1]	47	50	50	39	34	38	48	60	87	452	-

[1]LTA – Long-Term Averages (1964-2012)

Results and Discussion

Results in Table 2 shows average WW yields and its variation in trial in dependence to applied amounts and ratios of NPK nutrients in 20 different fertilizing treatments in 4 analyzed years. Average WW yield in the trial was 4.95 t ha^{-1}, ranging from 2.00 to 6.35 t ha^{-1}. Average mean yield deviation per years and fertilizing treatments from the overall mean was ±1.53 t ha^{-1} i.e. average mean relative yield deviation (CV) was 31%.

The effects of fertilization on WW yield were significant in all four years. The significantly lower yields in comparison to all other treatments were obtained on treatment without nutrient application (control), or on the treatments with only potassium applied (K_2 treatment), P_2K_2 and only P_2. In average for all years analyzed, the yield on these four treatments averaged 2.24 t ha^{-1}.

Considering the effect of a single application of nutrients, it can be concluded that N had the most significant influence on the WW yield. In average for all investigated years, applying only nitrogen (N_2) increased the yield in relation to control for over 2.6 t ha^{-1} (128%). On treatment with only phosphorus applied (P_2), yield decreased for 350 kg ha^{-1}, i.e. 17%, while the potassium didn't have any significant effect on the WW yield. When these three elements were used in dual combinations, it can be observed that fertilization with N and P (N_2P_2) had the significant advantage in relation to combined application of N and K (N_2K_2). However, both treatments were significantly better then the treatment P_2K_2.

The highest WW yield in the trial (6,35 t ha^{-1}) was obtained on the treatment $N_3P_3K_3$, but statistically equally high yields (α=0,05; i.e. over 5,81 ha^{-1}) were obtained on other triple fertilizing variants with the highest or moderate N doses, regardless to amounts of P and especially K. By applying all three nutrients at moderate or high N amounts (all treatments with $N_2P_xK_x$ and $N_3P_xK_x$; except $N_2P_1K_1$), yield ranged from 6,00 to 6,35 t ha^{-1}, i.e. varied only 350 kg. Statistical analysis didn't show any significant differences between these treatments. Higher doses of nutrients in these treatments were not economically viable.

In order to get more complete insight into the statistical significance of individual nutrients in WW mineral nutrition, single coefficients of correlations between increasing amounts of nutrients and WW yield were calculated (Table 2.). In all analyzed years, as well as in four years average, there was high and statistically significant (α=0.05) correlative relationship between N application and yield (r=0.82-0.94). Significant moderate correlations (0.50-0.61) was noticed between phosphorus application and WW yield, while correlation between amounts of potassium and yield was found not significant (r=0.27-0.39^{ns}).

Table 2. The effect of mineral nutrition on winter wheat grain yield (t ha^{-1})

Mineral nutrition treatment	kg ha^{-1} N	kg ha^{-1} P_2O_5	kg ha^{-1} K_2O	Years 2009	Years 2010	Years 2011	Years 2012	Average 2009-2012
Ø	0	0	0	2.09	2.53	1.72	1.83	2.04
N_2	100	0	0	4.00	5.38	4.40	4.84	4.66
P_2	0	100	0	2.50	2.85	2.25	1.95	2.39
K_2	0	0	100	1.87	2.52	2.01	1.59	2.00
N_2P_2	100	100	0	5.29	5.97	5.31	6.09	5.67
N_2K_2	100	0	100	4.19	5.23	4.76	5.40	4.89
P_2K_2	0	100	100	2.39	2.96	2.67	2.15	2.54
$N_1P_1K_1$	50	50	50	4.44	4.53	3.74	4.38	4.27
$N_1P_2K_1$	50	100	50	5.26	5.12	4.48	4.93	4.94
$N_1P_2K_2$	50	100	100	5.33	5.05	4.43	4.54	4.84
$N_2P_1K_1$	100	50	50	5.31	5.00	5.18	5.31	5.20
$N_2P_2K_1$	100	100	50	5.57	6.51	5.78	6.13	6.00
$N_2P_2K_2$	100	100	100	6.03	6.17	6.13	6.31	6.16
$N_2P_3K_1$	100	150	50	5.99	6.11	6.03	6.26	6.10
$N_2P_3K_3$	100	150	150	6.25	5.74	6.38	6.34	6.18
$N_3P_1K_1$	150	50	50	5.51	6.28	6.18	6.16	6.03
$N_3P_2K_1$	150	100	50	5.55	6.57	6.39	6.29	6.20
$N_3P_2K_2$	150	100	100	5.71	6.66	6.31	6.32	6.25
$N_3P_3K_2$	150	150	100	5.53	6.71	6.80	6.26	6.33
$N_3P_3K_3$	150	150	150	5.73	6.68	6.55	6.44	6.35
Average:				4.73	5.23	4.87	4.98	4.95
Max				6.25	6.71	6.80	6.44	6.35
Min				1.87	2.52	1.72	1.59	2.00
Max-Min				4.38	4.19	5.08	4.85	4.35
SD				1.42	1.44	1.63	1.72	1.53
CV (%)				30	28	34	34	31
		LSD	0.05	0.30	0.46	0.49	0.53	0.54
		LSD	0.01	0.37	0.52	0.60	0.68	0.72
		r	N	0.82*	0.94*	0.94*	0.92*	0.92*
		r	P_2O_5	0.61*	0.52*	0.59*	0.50*	0.56*
		r	K_2O	0.32	0.27	0.39	0.28	0.32

*significant on the level α=0.05

Nutrient efficiency in WW yields formation

Complete influence of certain nutrients on plants (nutrient efficiency) is not easy to determine because of their different effects at individual and combined application. According to Sarić and Jocić (1993), with combined application of nutrients, interaction among these nutrients occurs. For this reason, single nutrient effect can't be easily and precisely determined.

However, by using “difference method”, i.e. by comparing yield obtained at combined application and treatment where the one of the nutrient is omitted, approximate contribution of a missing element to yield formation could be determined.

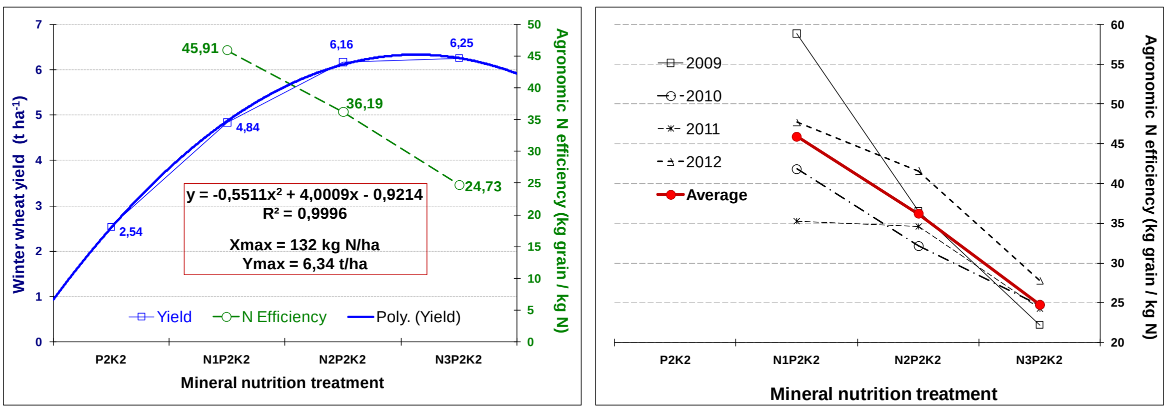
To determine the effect of each single nutrient to grain yield formation, method of difference between the yield achieved on treatment with balanced mineral nutrition ($N_2P_2K_2$) and dual combinations where one of the nutrient is omitted (N_2P_2, N_2K_2 and P_2K_2) was used. From the data presented in Table 3, it can be noticed that the nitrogen had the highest influence on yield increase per 1 kg of applied nutrient (in four years average 36.19 kg grain/1 kg N), followed with the phosphorus (12.65 kg grain/1 kg P_2O_5) and the potassium (4.95 kg grain/1 kg K_2O). Low values obtained with K application indicate good supply of this nutrient in Chernozem soil.

Table 3. Grain yield increasing with 1 kg of nutrients applied

Years	Grain Yield *($t\ ha^{-1}$)*				Yield increasing with 1 kg a.m. of nutrients applied *(kg grains / 1 kg nutrient)*		
	$N_2P_2K_2$	P_2K_2	N_2K_2	N_2P_2	N	P_2O_5	K_2O
2009	6.03	2.39	4.19	5.29	36.45	18.43	7.37
2010	6.17	2.96	5.23	5.97	32.15	9.43	2.05
2011	6.13	2.67	4.76	5.31	34.55	13.63	8.15
2012	6.31	2.15	5.40	6.09	41.59	9.10	2.22
Average	6.16	2.54	4.89	5.67	36.19	12.65	4.95

Influence of nitrogen fertilization doses on its efficiency

One of the main aims of this paper was to determine how different N fertilization levels influenced WW grain yield and nitrogen use efficiency (NUE). Determination of „*Agronomic N use Efficiency*“- AE_N (in this case effect of fertilization with increasing N doses on its efficiency) was done by the difference method, between yields on treatment P_2K_2 (taken as control) and $N_1P_2K_2$, $N_2P_2K_2$ and $N_3P_2K_2$. As can be seen from Graph 1, average yield increase with 1 kg of N applied was the highest on treatment $N_1P_2K_2$ (45.91 kg grain/1 kg N), then on treatment with moderate (36.19 kg/kg N), and the lowest at treatment with the highest N dose ($N_3P_2K_2$; 24.73 kg grain/1 kg N).



Graph 1. The effects of increasing amounts of N on grain yield and yield increasing with 1 kg of nitrogen applied - agronomic N use efficiency, average results (left) and for all four years (right)

Agronomic N use efficiency differed in years analysed (Graph 1, *right*). Highest AE_N values were in 2008/09 and 2011/12, and lower than average values in 2009/10 and 2010/11. Differences could be partly explained by the climate conditions. Year 2008/09 was somewhat hotter with total amount of precipitation near the LTA level, which favoured the nitrogen sorption, while in 2011/12 moisture reserve from February influenced intensive plant sorption of N applied at topdressing. Although March was dry, most N was already absorbed and more intensive absorption continued in wet April and May. In difference from these years, in extremely wet 2009/10 it is probably that the losses from N leaching were higher due to its removal to deeper soli layers.

In a specific year, as well as in average for all 4 years, AE_N had a decreasing tendency with increasement of N doses. The highest AE_N was on treatment with 50 kg N ha^{-1}, so this dose could be considered as the most rational in terms of lowest N losses and possible environmental pollution. However, in terms of mutual influence on the yield of winter wheat and nitrogen use efficiency, especially rational treatment was the one with 100 kg N ha^{-1} applied.

With moderate amounts of P and K (treatments $N_xP_2K_2$; Graph 1), the lowest N dose ($N_1P_2K_2$) increased grain yield for 2.3 t in relation to treatment P_2K_2, which was taken as control. Next N dose increased yield for additional 1.32 t of grain, while the highest N dose (treatment $N_3P_2K_2$) influenced non-significant yield increase of only 90 kg ha^{-1}. Average yield increasing for every additional dose of 50 kg N ha^{-1} was 1.25 t of grain ha^{-1}. However, the first nitrogen dose influenced the most intensive yield increase compared to control, while the effect of following N doses was less expressed. Influence of increasing N doses on WW yield had the saturating effect, i.e. followed the shape of quadratic regression curve (R^2=0.99). Based on the equation of this regression, at moderate P and K doses (100 kg ha^{-1}), theoretically calculated maximum regression grain yield of 6.34 t ha^{-1} can be achieved by applying 132 kg N ha^{-1} (Graph 1).

By analyzing the yield of winter wheat during the 50 years trial period, Kunzova and Hejcman (2009) stated that in the fifth decade of the experiment, average yield increase per 1 kg of N applied was 18,7 kg of grain. Similarly to our results, Vuković et al. (2008) for conditions of Croatia found that NUE values decreasing with higher intensity of N fertilization. NUE values ranged from 9.21 kg kg^{-1} with 300 kg N ha^{-1} up to 24.13 kg kg^{-1} on treatment with 100 kg N ha^{-1}. Authors concluded that better N efficiency was at fertilization with 100 kg N ha^{-1}, which can be considered as rational amount in terms of grain yield and harmful influence on environment. Also, NUE was influenced by soli type and climatic conditions, mainly by precipitation and temperature regime during vegetation period (Vuković et al., 2008).

According to Hatfield and Prueger (2004), NUE depended on soil moisture and N availability during vegetation. As well as in our research, Pepó (2007), concluded that the efficiency of fertilization was strongly modified by climatic conditions. Ortiz-Monasterio et al. (2001), Ortiz-Monasterio (2002) and Raun and Gordon (1999) stated that improvement in nutrition use efficiency by wheat can be achieved by two main strategies: application of more efficient cultivation practices (amount and time of fertilizers application, nutrient source, etc.) and by breeding of varieties with better efficiency of nutrients used. According to Malešević et al. (2008) in ten years investigated period, the yield of WW was increased with increasing amounts of N. The highest grain yield was achieved with the highest N dose of 180 kg ha^{-1}. However, average grain yield obtained at this treatment has not been significantly different from the yield achieved with 120 kg N ha^{-1}, so authors recommend it as optimal amount, which is in accordance with our results. Similar results are given in numerous other investigations. Therefore, Vrkoč et al. (1990), for conditions of Czech Republic recommend 120 kg N ha^{-1} as most suitable, even the highest yield was achieved by applying 160 kg N ha^{-1}.

Conclusions

In a 4-year investigation period, nitrogen had significantly the highest influence on the wheat grain yield. Fertilization with N only increase the yield compared to control up to 2.6 t ha^{-1} (128%), while fertilization with potassium only wasn't statistically significant.

When nutrients were used in dual combinations, fertilization with N and P (N_2P_2) had the significant advantage in relation to combined application of N and K (N_2K_2). However, both treatments were significantly better then the treatment P_2K_2.

The highest grain yield was obtained on treatment $N_3P_3K_3$, but statistically equally high yields (in range 6.00-6.35 t ha^{-1}) was achieved on all other triple nutrient combinations with highest or moderate N doses.

The highest yield increase with 1 kg of nutrient applied was with N, then P, and lowest with K. Agronomic N use efficiency had the decreasing tendency with increasing N doses. In terms of mutual influence on the yield of wheat and nitrogen use efficiency, especially rational treatment was the one with 100 kg of N ha^{-1} applied.

Influence of increasing N doses on wheat yield had the saturating effect, i.e. followed the shape of quadratic regression curve. Based on the equation of this regression, theoretically calculated maximum grain yield of 6.34 t ha^{-1} can be achieved by applying 132 kg N ha^{-1}.

Acknowledgment

The paper is the result of the project TR 031066 funded by the Ministry of Science and Technological Development of Republic of Serbia

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