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Effectiveness of nitrogen fertilization and application of microbial preparations in potato cultivation

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Abstract: This study examined the effectiveness of nitrogen fertilization and application of microbiological preparations in potato cultivation. The experiment factors were doses of nitrogen of 0, 60, 120, and 180 kg N ha^{-1} and microbial preparations of BactoFil B10, Effective Microorganisms EM, and UGmax. The amount of inorganic N in the 0–0.9 m soil layer before potato planting fluctuated from 63.5 to 80.4 kg N ha^{-1}, while after harvest it ranged from 44.4 to 119.7 kg N ha^{-1}. Nitrogen supply from mineralization during potato vegetation ranged from 36.1 to 46.3 kg N ha^{-1}. Each of the applied nitrogen doses caused a marked increase in potato-plant productivity in comparison with a smaller dose. Growing nitrogen doses decreased the value of the fertilization effectiveness index. Application of microbial preparations led to an increase in soil nitrogen content after plant harvesting and a lower uptake of N, diminishing the indices of NUE, NUpE, NAE, and NRF.

Key words: Microbial preparations, N fertilization, nitrogen use efficiency, potato

1. Introduction

Potato plant production systems are generally problematic in regards to nutrients, particularly nitrogen. Therefore, judicious fertilization in potato-plant production with nitrogen ensuring realization of agronomic, economic, and environmental goals poses a challenge to both agricultural science and practice. There have been numerous strategies of improving the effectiveness of nitrogen utilization by crops. In the opinion of Zebarth et al. (2009), these strategies may be divided into 2 categories: optimal nitrogen fertilization and limiting loss of this element.

Nitrogen is a crucial element in the process of plant growth and development and is also the main yield-forming element. However, numerous papers point to low effectiveness of applied nitrogen doses. In the case of potato plants, the coefficient of nitrogen utilization is on the level of 50% and is lower than in other plants (Vos, 2009). Effectiveness of fertilization diminishes with the use of growing nitrogen doses but increases when the dose is divided into presowing and top dressing (Westermann, 2005; Ruza et al., 2013). A low level of nitrogen utilization causes economic and ecological effects. Nitrogen, when not absorbed by crops or microorganisms, undergoes various processes that result in a considerable amount of it being lost.

The efficiency of nitrogen fertilization is most commonly assessed by the magnitude of either quantitative or qualitative changes of yield. Full evaluation of plant ability to transform the absorbed nitrogen to usable yield may be obtained through an analysis of such indices as N uptake, agronomic and physiological efficiency, N harvest index, and N apparent recovery fraction (Rahimizadeh et al., 2010; Abbasi et al., 2011). The efficiency of mineral fertilization is also markedly influenced by natural and organic fertilizers. Beneficial effects of these fertilizers result not only from improved soil structure, chemical, air-water, and sorption properties, but also biological properties (Truu et al., 2008). Application of exclusively mineral fertilizers and a great amount of pesticides may lead to disturbance of microbiological balance and consequently to soil degradation (Barabasz et al., 2002; Lancaster et al., 2006). Improvement of soil biological activity may be achieved through the application of microbial preparations. However, results of research on the effect of these preparations on crop yield and quality are not unanimous. Supporters of microbial preparation use prove their beneficial effect on crop yielding and soil properties (Stewart and Daly, 1999; Xu, 2000; Shah et al., 2001), whereas skeptics indicate that low reliability of the results is due to a short period of investigation, their local range, and methodological errors of conducted experiments (Priyadi et al., 2005; Vliet et al., 2006; Cóndor-Golec et al., 2007).

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These investigations were intended to determine the effect of nitrogen and microbial preparation dose in improving soil properties for the crop yield of potato tubers and shaping fertilization efficiency indices in the cultivation of edible potato.

2. Materials and methods

2.1. Experimental designs and agronomic management

The field experiment was conducted at the Experimental Station in Prusy, Poland (50°07′N and 20°05′E, 271 m a.s.l), in 2006–2008. The experiment was carried out in a split-block design in 4 replications. The experimental factors comprised nitrogen fertilization levels of 0, 60, 120, and 180 kg ha^{-1} and microbial preparations of BactoFil B10 (3 L ha^{-1}), Effective Microorganisms EM (3 L ha^{-1}), and Soil Fertilizer UGmax (0.9 L ha^{-1}) applied after the previous crop harvest and prior to spring soil cultivation. The treatments will be further referred to as N_0, N_{60}, N_{120}, and N_{180}, whereas the microbial preparations are respectively referred to as B, EM, and UGmax. B (AGRO.bio, Hungary) contains the following: *Azotobacter vinelandii*, *Azospirillum lipoferum*, *Bacillus megaterium*, *B. circulans*, *B. subtilis*, *Pseudomonas fluorescens*, macro/microelements, enzymes, and other active substances. EM (Greenland Technology EM, Poland) contains milk bacteria (*Lactobacillus casei*, *Streptococcus lactis*), photosynthetic bacteria (*Rhodopseudomonas palustrus*, *Rhodobacter sphaeroides*), yeast (*Saccharomyces albus*, *Candida utilis*), actinomycetes (*Streptomyces albus*, *S. griseus*), and molds (*Aspergillus oryzae*, *Mucor hiemalis*). UGmax (P.P.U.U BOGDAN, Poland) contains yeast, lactic acid bacteria, photosynthetic bacteria, *Azotobacter* spp., *Pseudomonas* spp., actinomycetes, and macro/microelements.

Nitrogen fertilization (urea) in the amount of 60 and 120 kg N ha^{-1} was applied before planting, whereas higher doses of 120 kg N ha^{-1} were applied before planting and the remaining part was spread as topdressing before the last ridging. Phosphorus (60 kg P_2O_5 ha^{-1}) and potassium (210 kg K_2O ha^{-1}) were used in early spring under cultivation. The previous crop before potato was winter wheat, and after harvest, white mustard was sown as the catch crop. The harvested plot was 24.0 m^2. Tubers of medium early edible potato cultivar Satina were planted in the second decade of April with 75 × 35 cm row spacing.

2.2. Soil and meteorological conditions

The soil type of the experimental field was a Luvic Chernozem developed from loess. The soil arable layer was slightly acidic with a high magnesium concentration, while phosphorus and potassium concentrations were moderate.

During the vegetation period in 2006, there was 279 mm of rainfall and the average temperature was 15.7 °C. Unfavorable weather conditions, due to very high air temperature and insufficient rainfall, were registered in July, especially during the setting and development of tubers. In 2007, the period from April to September was characterized by the highest mean air temperature (16.1 °C) and rainfall (541 mm). Therefore, an excessive amount of rainfall was noted during tuber maturation. On the other hand, the period of potato vegetation in 2008 was characterized by the lowest air temperature recorded over the 3-year cycle of research (15.2 °C). Measured rainfall (387 mm) approximated to a multiannual average but was unevenly distributed. Notably, a particularly high rainfall deficiency occurred during the period from emergence to the beginning of the tuber setting stage.

2.3. Plant and soil analysis

Soil samples for the assessment of the content of mineral nitrogen (N-NO_3 and N-NH_4) were taken before potato planting and harvest from the 0–0.9 m soil layer. The soil samples from 4 places in a plot were combined in 1 sample and kept frozen until analysis. Analysis of nitrate and ammonium ion content was conducted by colorimetric method.

The amount of nitrogen originating from mineralization for each year and experimental treatment was determined as the difference between the content of mineral nitrogen in soil before planting and nitrogen absorbed by the potato plants in the plants without fertilization (0 kg N ha^{-1}) and mineral nitrogen in the soil after harvest (Huggins and Pan, 1993). Nitrogen concentrations in the plant material were assessed using Kjeldahl's method.

The following parameters were calculated for each treatment:

1. N use efficiency (NUE; kg kg^{-1}) as the ratio of tuber yield dry weight to N supply (the sum of mineral nitrogen in the soil before planting, mineralized N, and N fertilizer).
2. N uptake efficiency (NUpE; kg kg^{-1}) as the ratio of N uptake by plants to N supply.
3. N utilization efficiency (NUtE; kg kg^{-1}) as the ratio of dry weight of plants to N uptake.
4. N harvest index (NHI; %) as the ratio of N in tuber to N uptake by plant.
5. N agronomic efficiency (NAE; kg kg^{-1}) as the ratio of (tuber yield of fresh mass at N_x – tuber yield of fresh mass at N_0) to applied N at N_x.
6. N physiological efficiency (NPE; kg kg^{-1}) as the ratio of (total dry weight of plants at N_x – total dry weight of plants at N_0) to (N uptake by plant at N_x – N uptake by plant at N_0).
7. N apparent recovery fraction (NRF; %) as the ratio of (N uptake by plant at N_x – N uptake by plant at N_0) to N applied at N_x.

2.4. Statistics

The results were statistically analyzed by analysis of variance using the AWAR program. Least significant differences (LSDs) for the N efficiency parameters were verified using Tukey's test at significance level $P < 0.05$.

3. Results

3.1. Soil N supply

Mineral nitrogen supply of the 0.9 m depth fluctuated in the individual years from 63.5 to 80.4 kg N ha^{-1} in spring before potato planting, whereas after the harvest fluctuation, it was from 44.4 to 119.7 kg N ha^{-1} (Table 1). Application of microbial preparations contributed to a significant increase in mineral nitrogen concentrations in the soil after the harvest. The greatest difference between nitrogen concentration in soil before planting and after harvest was registered with the UGmax treatments (average: 14.7 kg N ha^{-1}). It was smaller after the use of B and EM preparations, whereas the smallest difference was observed with the control (average 8.8 kg N ha^{-1}). The level of nitrogen mineral fertilization also markedly affected the content of this element in soil after the harvest. The least amount of mineral nitrogen was noted in the N_0 plots, whereas the biggest quantities followed the application of 180 kg N ha^{-1} and 117.8 kg N ha^{-1}, respectively. The quantity of soil mineralized nitrogen in the individual years of the experiment was not significantly different and fluctuated from 40.7 to 43.0 kg N ha^{-1} (Table 1). Although application of microbial preparations caused increased inflow of mineralized nitrogen, the differences were not statistically significant. A notable increase in the amount of nitrogen mineralized nitrogen was registered only in 2008 following the application of B preparation.

3.2. Productivity of plants

The yield of potato tuber fresh mass ranged from 18.6 to 44.2 t ha^{-1} and tuber dry weight yield ranged from 4.25 to 8.94 t ha^{-1}, whereas biomass of the whole plants ranged from 4.68 to 10.09 t ha^{-1} (Table 2). Productivity of potato plants depended on nitrogen fertilization level. Each nitrogen dose caused a significant increase in plant yield in comparison with a smaller dose. Application of 60 kg N ha^{-1} ensured increases in both fresh and dry mass of tubers by 53.5% and 50.9%, respectively, and in whole plants by 50.4% in comparison with the control plots. Enlarging the nitrogen quantity to the level of 120 kg N ha^{-1} led to greater potato plant productivity of an average of 25%, whereas application of 180 kg N ha^{-1} in comparison with lower dose N_{120} increased the yield of tuber fresh mass only 11.7%, dry tuber weight yield 8.0%, and whole potato plant yield 7.3%. Therefore, the effect of microbial preparations on productivity of potato plants was diversified. Application of B preparation contributed to a marked diminishing of fresh mass yield of tubers, the use of EM preparation resulted in diminished yield of fresh and dry tuber mass, and application of UGmax preparation led to diminishing

Table 1. Mineral nitrogen ($N\text{-}NO_3 + N\text{-}NH_4$) in soil and N mineralized (kg ha^{-1}) at 0–0.9 m.

Treatment	Year 2006			2007			2008			Mean		
	N_{min} in soil		N mineralized	N_{min} in soil		N mineralized	N_{min} in soil		N mineralized	N_{min} in soil		N mineralized
	planting	harvest		planting	harvest		planting	harvest		planting	harvest	
Microbiological preparation												
Control	68.6	86.4	37.7	71.1	74.7	37.9	79.1	84.0	36.1	72.9	81.7	37.3
B	75.8	90.3	39.7	72.7	86.7	44.7	79.5	86.0	45.8	76.0	87.7	42.6
EM	72.9	86.7	41.2	76.8	87.7	43.1	78.8	85.3	43.5	76.2	86.6	43.4
UGmax	72.6	89.7	44.4	63.5	80.9	46.3	80.4	90.0	37.9	72.2	86.9	42.8
$LSD_{p=0.05}$	n.s.	3.4	n.s.	n.s.	5.4	n.s.	n.s.	n.s.	8.2	n.s.	2.3	n.s.
N dose (kg ha^{-1})												
N_0	72.1	52.7		71.4	44.4		79.7	54.5		74.4	50.6	
N_{60}	72.9	79.8		70.9	75.7		79.7	78.0		74.5	77.9	
N_{120}	71.4	100.8		70.9	92.9		79.2	95.9		73.8	96.5	
N_{180}	73.5	119.7		70.9	117.0		79.2	116.8		74.6	117.8	
$LSD_{p=0.05}$	n.s.	2.7		n.s.	3.0		n.s.	4.4		n.s.	1.5	
Mean	72.5	88.3	40.7	71.0	82.5	43.0	79.5	86.3	40.8			

$LSD_{p=0.05}$ for N mineralization – n.s.
n.s.: Not a significant difference.

Table 2. Tuber yield (fresh weight) and dry weight of tubers and total plants (t ha^{-1}).

Treatment	Year 2006 Tuber yield	Dry weight Tuber	Plant	2007 Tuber yield	Dry weight Tuber	Plant	2008 Tuber yield	Dry weight Tuber	Plant	Mean Tuber yield	Dry weight Tuber	Plant
Microbial preparation												
Control	33.9	7.35	7.95	33.5	6.96	7.85	35.0	7.11	7.48	34.1	7.14	7.76
B	29.8	6.80	7.37	34.4	7.18	8.04	34.5	7.32	8.08	32.5	7.10	7.83
EM	30.6	6.57	7.11	33.2	6.84	7.76	32.4	7.18	7.96	33.2	6.86	7.61
UGmax	33.4	7.51	8.13	32.6	6.68	7.59	33.7	6.74	7.05	34.4	6.98	7.59
$LSD_{p=0.05}$	1.1	0.24	0.26	0.9	0.35	n.s.	1.9	n.s.	0.56	0.7	0.19	0.22
N dose (kg ha^{-1})												
N_0	18.6	4.25	4.68	20.1	4.34	4.84	21.1	4.54	4.89	20.2	4.38	4.80
N_{60}	29.6	6.66	7.25	31.1	6.55	7.35	31.7	6.60	7.07	31.0	6.61	7.22
N_{120}	37.8	8.39	9.04	38.3	7.89	8.95	38.9	8.38	9.17	39.2	8.22	9.05
N_{180}	41.6	8.94	9.60	44.2	8.88	10.1	43.9	8.82	9.44	43.8	8.88	9.71
$LSD_{p=0.05}$	0.7	0.20	0.23	0.8	0.47	0.56	1.5	0.63	0.67	0.5	0.17	0.21
Mean	31.9	7.06	7.64	33.4	6.92	7.81	33.9	7.09	7.64			

$LSD_{p=0.05}$ for: tuber yield – 0.7
dry weight of tuber – n.s.
dry weight of plant – n.s.
n.s.: Not a significant difference.

biomass of the whole plants. A positive result of microbial preparation application was seen only in the control plots at N_0 (Figure 1). On the other hand, preparations used in the plots of N_{120} and N_{180} caused a significant diminishing of tuber yield in comparison with the control. The weather conditions during the period of investigations markedly affected only the yield of tuber fresh mass. The biggest yields were produced in 2007 and 2008, with the 2006 yield being significantly lower. The factor limiting potato yield in 2006 was lower precipitation as compared to the other years.

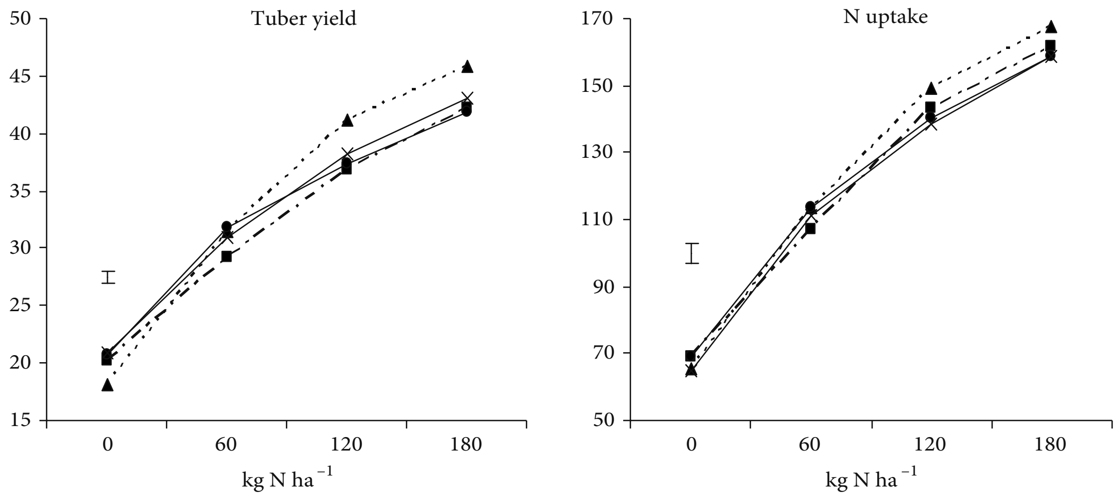

Figure 1. Tuber yield (t ha^{-1}) and total plant N uptake (kg ha^{-1}). Bars represent the $LSD_{0.05}$ for mean values' comparison. Effect of microbial preparations application: control – ▲ –; B – ▪ –; EM – ● –; UGmax – × –.

3.3. N uptake

Nitrogen uptake with potato plant biomass was increased with growing levels of nitrogen fertilization from 67 kg N ha^{-1} in the control to 162 kg N ha^{-1} with application of 180 kg N ha^{-1} (Table 3). The influence of microbial preparations on nitrogen uptake was diversified over the years. However, the average for the years' nitrogen uptake in the plants when B, EM, and UGmax preparations were applied was markedly lower than the uptake in the control. Moreover, the results revealed an interaction between the levels of nitrogen fertilization and microbial preparations. Application of the preparations caused a significant decline in nitrogen uptake by potato plants with N_{120} and N_{180} applications (Figure 1). Nitrogen uptake and potato tuber yield increased with increasing nitrogen fertilization level from 62 kg N ha^{-1} (control, N_0) to 150 kg N ha^{-1} (N_{180} application). Application of B and EM microbial preparations contributed to diminished nitrogen uptake with tuber yield by about 5% and 6% as compared to when UGmax was used.

3.4. Nitrogen efficiency

NUE depended notably on the dose of nitrogen and microbial preparation (Table 4). The highest value of NUE index was noted in N_0 and N_{60} (37.8 and 37.5 kg kg^{-1}). Each subsequent increased in fertilization level caused a significant decrease in NUE. The lowest NUE value, on average 30.1 kg kg^{-1}, was noted in plots receiving 180 kg N ha^{-1}. Application of B and EM microbial preparations resulted in a markedly decreased in NUE. The effect of microbial preparations on NUE index value was diverse in the individual years of the experiment and fertilizer treatments. A positive effect of microbial preparations' application was registered only in N_0 plants after application of EM and UGmax preparations (Figure 2). The efficiency of nitrogen use in N_{120} and N_{180} treatments following microbial preparations application was markedly lower than in the control.

NUpE differed from NUE (Table 4). The weather conditions in the individual years of the research had a significant influence on NUpE index value. The highest share of absorbed nitrogen with reference to nitrogen amount available to potato plants, on average 0.62 kg kg^{-1}, was noted in 2007, which was characterized by the highest rainfall amount in the whole cycle. In 2006 and 2008, which were characterized by a small amount of rainfall, the value of NUpE was 0.58 kg kg^{-1}. The highest NUpE in fertilizer application was registered following fertilization with 60 kg N ha^{-1}, while each subsequent increase in fertilizer dose resulted in a significant diminishing of this index. The application of microbial preparations contributed to a decrease in NUtE values on average by 0.04 kg kg^{-1}. Negative effect of microbial preparations on

Table 3. Nitrogen uptake (kg ha^{-1}).

Treatment	Year						Mean	
	2006		2007		2008			
	N uptake		N uptake		N uptake		N uptake	
	Tuber	Total	Tuber	Total	Tuber	Total	Tuber	Total
Microbial preparation								
Control	116	123	114	124	120	124	117	124
B	102	109	117	128	115	125	111	121
EM	106	113	115	127	111	121	111	120
UGmax	111	119	108	120	112	116	110	118
$LSD_{p=0.05}$	5	4	6	7	7	6	3	3
N dose (kg ha^{-1})								
N_0	61	65	65	70	62	66	62	67
N_{60}	100	107	105	114	107	113	104	111
N_{120}	129	137	131	143	138	148	132	143
N_{180}	145	154	155	171	151	160	150	162
$LSD_{p=0.05}$	6	3	6	8	4	8	2	3
Mean	109	116	114	125	115	122		

$LSD_{p=0.05}$ for: N tuber uptake – 3
N total uptake – 2

Table 4. N use efficiency (NUE), N uptake efficiency (NUpE), N utilization efficiency (NUtE), and N harvest index (NHI).

Treatment	Microbial preparation				N dose (kg ha^{-1})				Mean
	Control	B	EM	UGmax	N_0	N_{60}	N_{120}	N_{180}	
NUE (kg kg^{-1})									
2006	37.6	34.3	33.0	37.6	37.6	38.4	36.1	30.5	35.6
2007	35.9	35.4	33.6	34.9	38.1	37.7	33.7	30.2	34.9
2008	35.2	35.3	34.7	33.4	37.6	36.6	34.9	29.4	34.6
$LSD_{p=0.05}$	1.7				1.7				
Mean	36.2	35.0	33.8	35.3	37.8	37.5	34.9	30.1	
$LSD_{p=0.05}$	0.9				0.9				n.s.
NUpE (kg kg^{-1})									
2006	0.63	0.54	0.56	0.58	0.58	0.62	0.59	0.53	0.58
2007	0.63	0.62	0.61	0.60	0.61	0.66	0.61	0.58	0.62
2008	0.61	0.58	0.57	0.56	0.55	0.63	0.62	0.53	0.58
$LSD_{p=0.05}$	0.03				0.02				
Mean	0.62	0.58	0.58	0.58	0.58	0.64	0.61	0.55	
$LSD_{p=0.05}$	0.02				0.01				0.02
NUtE (kg kg^{-1})									
2006	65.0	68.6	63.4	70.3	71.9	67.2	66.1	62.3	66.9
2007	63.8	63.7	62.1	65.2	69.3	64.0	62.5	59.0	63.7
2008	61.2	66.9	67.0	62.9	74.0	62.7	62.1	59.2	64.5
$LSD_{p=0.05}$	2.8				2.6				
Mean	63.3	66.4	64.2	66.1	71.7	64.6	63.6	60.2	
$LSD_{p=0.05}$	1.5				1.6				1.2
NHI (%)									
2006	93.8	93.4	93.0	93.3	92.8	92.9	93.9	94.1	93.4
2007	92.3	91.6	90.8	90.6	92.5	91.1	91.1	90.4	91.3
2008	96.3	92.7	91.9	96.5	94.2	95.0	93.6	94.6	94.4
$LSD_{p=0.05}$	2.1				1.8				
Mean	94.1	92.6	91.8	93.5	93.2	93.0	92.9	93.1	
$LSD_{p=0.05}$	1.1				n.s.				0.9

n.s.: Not a significant difference.

nitrogen-uptake efficiency was particularly evident in the years with lower amounts of precipitations. A significantly unfavorable effect of microbial preparations on NUpE was noted in all nitrogen fertilizer plots, irrespective of applied dose (Figure 2).

NUtE ranged from 59.0 to 74.0 kg kg^{-1} (Table 4). The advantageous influence of microbial preparations on NUtE was evident in the years with lower amounts of precipitation. Significant increases in NUtE values were registered following the application of B and UGmax preparations in 2006, whereas in 2008 after the application of B and EM preparations, NUtE in N_0 was 71.7 kg kg^{-1}. Each of the applied nitrogen doses caused a marked decline in NUtE index value. The lowest NUtE on average was 60.2 kg kg^{-1} and was observed with N_{180} application. In the control, N_0, a higher NUtE was noted than following the application of microbial preparations (Figure 2). Beneficial effect on this index value following EM preparation application was also observed in N_{60} and N_{120} applications.

The NHI index, describing the share of nitrogen accumulated in tuber yield in relation to total nitrogen uptake by potato plants, ranged from 90.4% to 96.5% (Table 4). The level of nitrogen fertilization did not diversify NHI

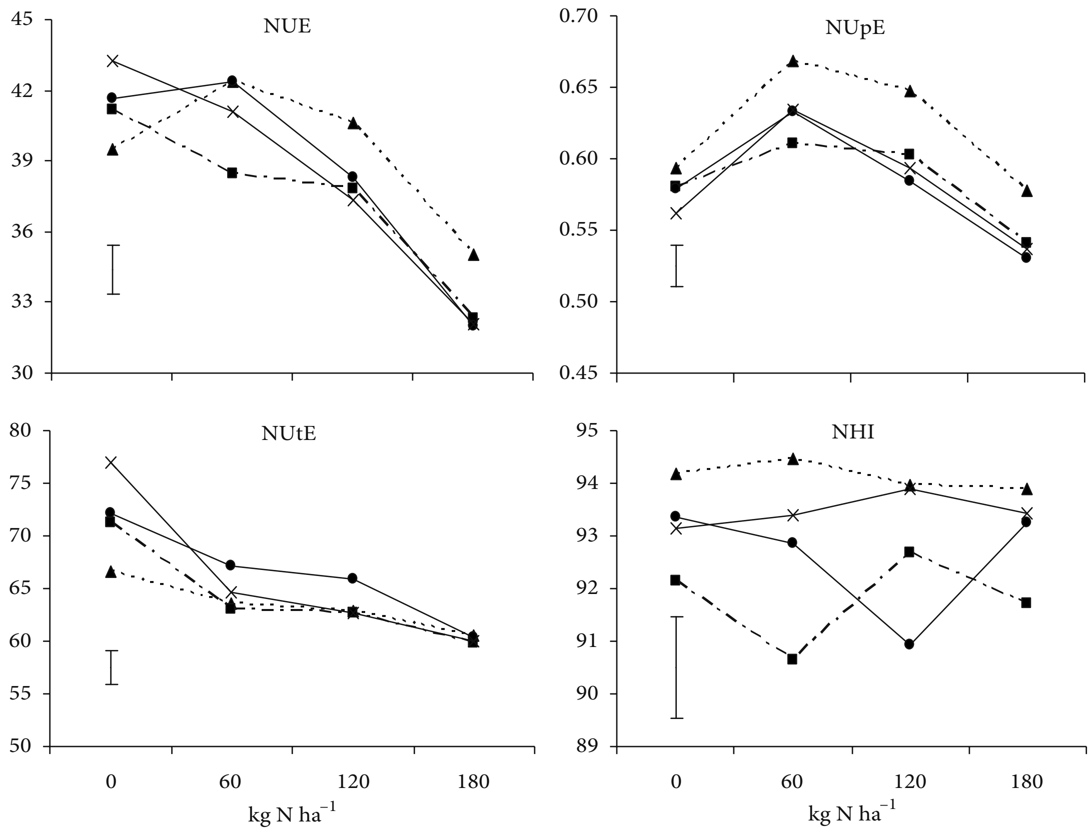

Figure 2. N use efficiency (NUE, kg kg^{-1}); N uptake efficiency (NUpE, kg kg^{-1}); N utilization efficiency (NUtE, kg kg^{-1}); N harvest index (NHI, %). Bars represent the $LSD_{0.05}$ for mean values' comparison. Effect of microbial preparations application: control – ▲ –; B – ▪ –; EM – ● –; UGmax – × –.

index values. Application of microbial preparations also had a marked influence on NHI index values. Application of B and EM preparations notably decreased this index value, particularly in 2008.

NAE expresses the increase in tuber yield per 1 kg of nitrogen used in fertilizers. The highest NAE, on average 181 kg kg^{-1}, was registered in the N_{60} application, whereas the significantly smallest in N_{120} plants was on average 153 kg kg^{-1} and the smallest in N_{180} plants was 130 kg kg^{-1} (Table 5). The weather conditions in the respective potato vegetation seasons did not affect NAE directly. On the other hand, application of microbial preparations had a marked influence on this index value. Each of the microbial preparations applied in potato cultivation decreased NAE (Figure 3). The greatest decline in NAE, on average by 52 kg kg N^{-1}, was noted in the treatments where EM preparation was used. The lowest, on average by 41 kg kg^{-1}, was following the application of B preparation.

NPE, defined as tuber dry mass yield increment per nitrogen unit absorbed by plants, depended both on the experimental factors and the weather conditions (Table 5). In N_{60} and N_{120} treatments, physiological effectiveness of N was similar, at 54.0 and 56.6 kg kg^{-1}, respectively. A significantly lower NPE, on average 51.8 kg kg^{-1}, was registered after the application 180 kg N ha^{-1}. In potato plants for which microbial preparations were used, NPE was similar to NAE. EM and UGmax preparations notably decreased NPE by 4.9 and 10.1 kg kg^{-1}, respectively, whereas B preparation did not have any influence on this index value. Application of UGmax preparation led to a decrease in NPE in N_{60} and N_{120} plants, whereas application of B preparation influenced a decrease in NPE only in the N_{60} treatment (Figure 3). The highest NPE over the 3-year period of investigations, on average 59.0 kg kg^{-1}, was registered in the vegetation season with the lowest precipitation amount (2006), and the lowest, on average 48.7 kg kg^{-1}, was in 2008, characterized by rainfall deficiency in the initial period of plant development and at the stage of tuber formation.

NRF ranged from 49.6 to 78.0% (Table 5). The biggest quantity of nitrogen applied in fertilizers, on average 74.8%, was recovered by plants fertilized with a dose of 60 kg N ha^{-1}. Each increase in nitrogen dose led to a notably worse recovery of this element. Potato plants fertilized with a dose of 120 kg N ha^{-1} used up 63.1% of the applied nitrogen,

Table 5. N physiological efficiency (NPE), N agronomic efficiency (NAE), N apparent recovery fraction (NRF)

Treatment	Microbial preparation				N dose (kg ha^{-1})			Mean
	Control	AM	EM	UGmax	N_{60}	N_{120}	N_{180}	
NPE (kg kg^{-1})								
2006	62.7	66.3	53.9	53.2	60.4	61.6	55.0	59.0
2007	57.7	60.9	51.1	49.2	55.9	56.2	52.0	54.7
2008	55.6	45.5	50.7	43.2	45.7	52.0	48.5	48.7
$LSD_{p=0.05}$	n.s.				5.9			
Mean	58.6	57.6	51.9	48.5	54.0	56.6	51.8	
$LSD_{p=0.05}$	5.8				2.9			5.3
NAE (kg kg^{-1})								
2006	198	139	139	153	184	160	128	157
2007	168	181	142	134	183	152	134	156
2008	202	123	130	147	177	148	127	151
$LSD_{p=0.05}$	20				n.s.			
Mean	189	148	137	145	181	153	130	
$LSD_{p=0.05}$	10				6			n.s.
NRF (%)								
2006	71.1	50.5	55.6	64.3	71.5	60.1	49.6	60.4
2007	62.5	69.5	60.1	64.0	74.7	61.2	56.3	64.0
2008	73.4	64.6	64.2	62.1	78.1	68.1	52.0	66.1
$LSD_{p=0.05}$	10.3				4.9			
Mean	69.0	61.5	60.0	63.5	74.8	63.1	52.6	
$LSD_{p=0.05}$	5.4				2.8			4.7

n.s.: Not a significant difference.

whereas those fertilized with 180 kg N ha^{-1} respectively used 52.6%. The application of microbial preparations led to a lower nitrogen recovery from fertilizers of between 5.5 and 9.0%. With B preparation application, a notable decrease in NRF was observed in N_{60} and N_{120} treatments, and for EM preparation, a notable decrease was seen in the N_{120} treatment (Figure 3). An especially unfavorable effect of B and EM preparations on nitrogen recovery was apparent in 2006, whereas for UGmax preparation it was apparent in 2008.

Potato tuber yield was most strongly correlated with NUtE (r = –0.63) and NUE (r = –0.50), and to a lesser degree with NRF (r = –0.39) and NAE (r = –0.26) (Table 6). Moreover, the investigations demonstrated a strict dependence between NUE and the other fertilization efficiency indices, except NHI, but also a strict dependence between NUpE and NRF (r = 0.90) and NUpE and NAE (r = 0.73). Nitrogen utilization efficiency (NUtE) revealed a strict relationship with NPE (r = 0.69) and NAE (r = 0.27). NAE was significantly correlated with NRF (r = 0.78) and NPE (r = 0.43).

4. Discussion

The main sources of nitrogen for crops, except Fabaceae, are mineral and organic fertilizers and mineralization of organic matter. Sullivan et al. (1999) estimated that soil enrichment in N from mineralization fluctuates from 50 to 130 kg N ha^{-1} depending on the soil kind and crop cultivation system. The estimates concerning N quota originating from mineralization, based on the assumption that about 2% of total organic N occurring in the soil undergoes mineralization, are encumbered with serious errors (Schepers and Mosier, 1991). In the author's own investigations, N amount estimated on the basis of inorganic N content before potato planting and after harvest and N uptakes by plants in N_0 potatoes was on a low level, i.e. from 36.1 to 46.3 kg N ha^{-1}. Moreover, the amount of mineralized N in respective years of the experiment was not significantly diversified. Rodriguez et al. (2001) also revealed a constant level of mineralization intensity, on average 0.71 kg N ha^{-1} day^{-1}, over a 4-year period of investigations. According to Jenkinson (1990), nitrogen mineralization is maximal when the soil

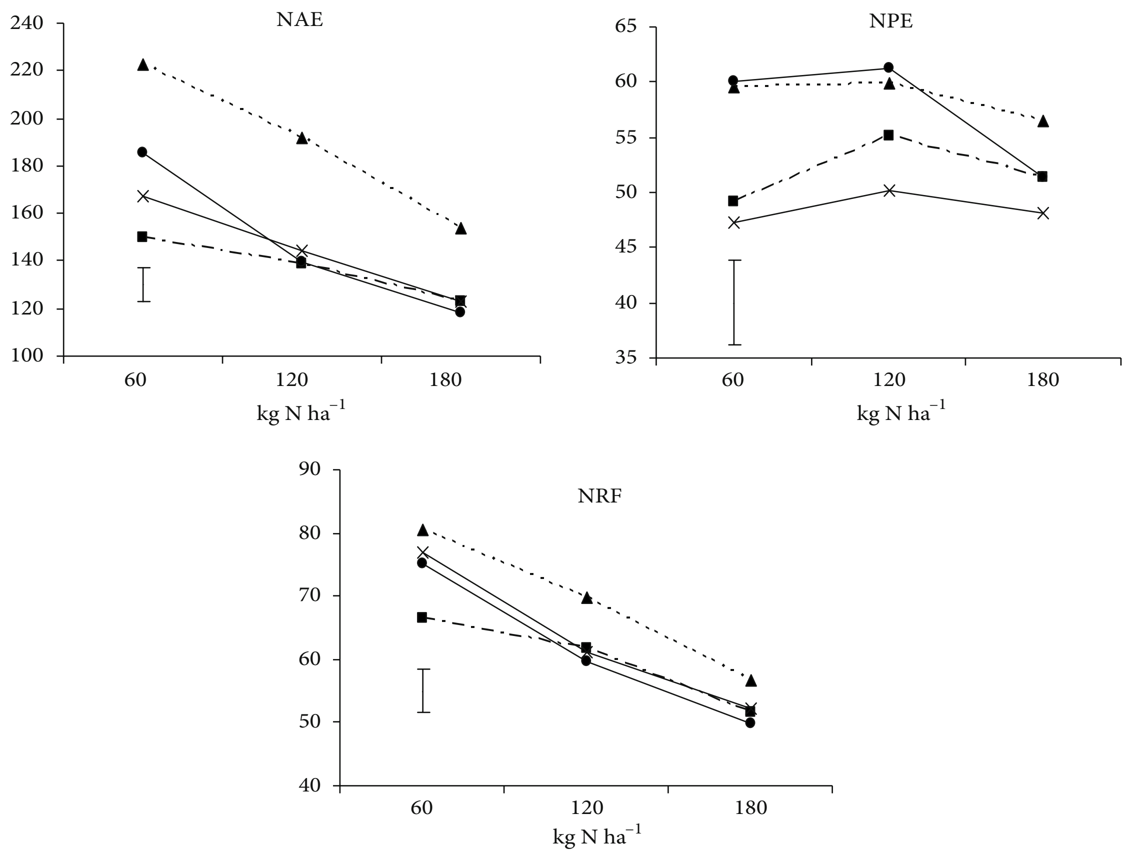

Figure 3. N agronomic efficiency (NAE, kg kg^{-1}); N physiological efficiency (NPE, kg kg^{-1}); N apparent recovery fraction (NRF, %). Bars represent the $LSD_{0.05}$ for mean values' comparison. Effect of microbial preparations application: control – ▲ –; B – ▪ –; EM – ● –; UGmax – × –.

moisture is close to field moisture, whereas an excessive or insufficient moistness limits the intensity of the process. According to Zebarth et al. (2004a), precise determination of mineralized N supply is difficult due to N-NO_3 leaching and denitrification, but also uneven distribution of precipitations, which may intensify mineralization during potato plant maturing. The significance of the weather conditions' influence on the supply of mineralized nitrogen was also revealed by Kolberg et al. (1999) and Sieling et al. (1999). The course of the mineralization process also depends on soil microbiological activity. Bloem et al. (1994) revealed a larger mass of soil microorganisms and, by 31%, a larger amount of mineralized nitrogen in the integrated than in the traditional farming system. In the presented investigations, an attempt at increasing the soil microbiological activity through the application of microbial preparations led to an increased supply of mineralized N, on average for plants by 5.6 kg ha^{-1}, yet the differences were not statistically significant. The result of increasing the quota of nitrogen available to plants following the application of microbial preparations was a notable increment of tuber yield and this element's uptake in the plots not fertilized with nitrogen, N_0. Total nitrogen amount taken up by the N_0 plants without the application of microbial preparations was 65.4 kg N ha^{-1}, while after the application of preparations it was greater, on average by 2.3 kg N ha^{-1}. A beneficial effect of microbial preparations on organic matter mineralization and potato yield makes it a good recommendation to use these preparations in potato cultivation fertilized with small nitrogen doses and in organic production. Nitrogen uptake by potato plants in the unfertilized plots, as reported in the literature on the subject, is greatly variable and depends on the cultivar and climatic and environmental conditions affecting N mineralization and losses. Zebarth (2005) revealed N uptake ranging from 60 to 91 kg N ha^{-1}. In the experiments conducted by Vos (1997), N uptake fluctuated from 55 to 110 kg N ha^{-1}, whereas Riley (2000) demonstrated N uptake on the level of 46 kg N ha^{-1}.

Potato plant productivity and N uptake both for tuber yield and whole potato plant mass depended significantly on the nitrogen fertilization level. Each of the applied nitrogen doses within the range of 0–180 kg N ha^{-1} caused a marked increase in plant yield and N uptake in comparison

Table 6. Correlation coefficient among tuber yield, N use efficiency (NUE), N uptake efficiency (NUpE), N utilization efficiency (NUtE), N harvest index (NHI), N agronomic efficiency (NAE), N physiological efficiency (NPE), and N apparent recovery fraction (NRF).

	Tuber yield	NUE	NUpE	NUtE	NHI	NAE	NPE
NUE	–0.50**						
NUpE	–0.03	0.60**					
NUtE	–0.63**	0.67**	–0.12				
NHI	0.01	0.03	–0.17*	–0.11			
NAE	–0.26**	0.80**	0.73**	0.27**	0.10		
NPE	–0.04	0.37**	0.04	0.69**	–0.18*	0.43**	
NRF	–0.39**	0.80**	0.90**	0.12	0.03	0.78**	–0.01

*: Significant at 5% level of probability, **: significant at 1% level of probability.

with a lower dose. Zebarth et al. (2004a) obtained different results. In 2 out of 3 years of investigations, they revealed a significant increase in plant productivity in the plants fertilized to the level of 80 kg N ha^{-1}. Higher doses, i.e. 120, 160, and 200 kg N ha^{-1}, caused a slight increase or decline in dry weight accumulation. On the other hand, in the research of Jamaati-e-Somarin et al. (2010), a marked increase in plant productivity expressed as increase in plant dry weight occurred to a fertilization level of 160 kg N ha^{-1}. Moreover, the authors of both investigations cited above revealed that N uptake by potato plants was growing in a linear fashion with each subsequent nitrogen dose.

Unused nitrogen by crops may become a source of nitrate environmental burden. In this author's own studies, a markedly bigger amount of inorganic N after potato harvest than prior to planting was registered in plants fertilized with 120 and 180 kg N ha^{-1}. Application of microbial preparations also caused an increase in mineral nitrogen amount in soil after potato harvesting. Errebhi et al. (1998) demonstrated the same amount of N-NO_3 before planting and after potato harvest in 1 out of 2 years of research, independently of fertilization level (0–135 kg N ha^{-1}). Zebarth et al. (2004a), in 2 out of 3 years of experiment, also did not find any significant N-NO_3 concentration in the soil after harvesting potatoes fertilized in a range from 0 to 200 kg N ha^{-1}. A great amount of inorganic nitrogen in the soil after plant harvest may evidence, among other things, a low apparent NRF. In the presented experiment, the value of the NRF index fluctuated widely from 49.6% to 78.1% depending on the year of the experiment and experimental factors. Significantly lower N apparent recovery fraction was noted in the plants for which microbial preparations were applied than in the control. This resulted from a greater N uptake after the application of microbial preparations in N_0 plants and a smaller N uptake in N_{60}, N_{120}, and N_{180} treatments. The result also might have been due to a partial N immobilization by soil microorganisms during intensive growth and development of potato plants and subsequent N mineralization during the period of plant maturation and harvest. This conflicts with the opinion of Jingguo and Bakken (1997) about a lack of nitrogen biological immobilization by soil microorganisms. NRF with fertilizer application diminished from 74.8% in N_{60} to 52.6% in N_{180} plants. Jamaati-e-Somarin et al. (2010) obtained approximate values of the NRF index of 69.3% at 80 kg N ha^{-1} and 47.1% and 50.3% at 160 and 200 kg N ha^{-1}. Darwish et al. (2006) noted N recovery fraction on the level of 61% in plants fertilized with 125 kg N ha^{-1}, whereas following the application of 500 kg N ha^{-1} it was only 31%. On the basis of regression analysis, Li et al. (2003) demonstrated the highest NRF value for a fertilization level of 130 kg N ha^{-1}. Moreover, the authors found a linear dependence between dose of N ha^{-1} and unutilized amounts of nitrogen.

In the opinion of de Willingen and van Noordwijk (1987), the value of the NUpE index depends on physiological and morphological factors, while according to Marschner (1995), NUtE value depends on a plant's ability to absorb, transport, store, and remobilize N.

The effect of nitrogen fertilization on shaping NUpE is not unanimously agreed upon in the literature. Zebarth et al. (2004a, 2004b) demonstrated a lack of significant effect of nitrogen fertilization level on this index value, whereas the research of Tyler et al. (1983) and Zvomuya et al. (2002) revealed a decreasing NUpE value under the influence of growing nitrogen doses. This author's own experiments confirmed the dependence and demonstrated a notable effect of the weather conditions on shaping the NUpE index. In the years with lower rainfall during potato vegetation, i.e. 2006 and 2008, the value of the NUpE index was lower than in 2007, which was characterized by greater rainfall amount. A lower NUpE value under conditions of rainfall deficiency and at nitrogen top dressing was also registered by Zebarth et al. (2004a). NUtE was decreasing in the research of the above-mentioned authors with growing nitrogen doses. In this author's own studies, NUtE was diminishing from 71.7 kg kg^{-1} in the N_0 treatment to 60.2 kg kg^{-1} in the N_{180} treatment. On the other hand, in research conducted by Errebhi et al. (1999), NUtE in the plants receiving 225 kg N ha^{-1} was similar to or slightly lower than in the unfertilized plants.

An important indicator of nitrogen fertilization efficiency is NAE. In the present experiment, the increment of tuber fresh mass yield per 1 kg of applied nitrogen was high at 181 kg in N_{60} plants, 153 kg in N_{120} plants, and 130 kg in N_{180} plants. A markedly lower NAE was registered by Jamaati-e-Somarin et al. (2010). For potato fertilization within the range from 80 to 200 kg N ha^{-1}, they demonstrated tuber yield growth from 121.19 kg ha^{-1} to 21.6 kg ha^{-1}, respectively. On the other hand, in research conducted by Shahbazi et al. (2009), NAE in plants fertilized with 80 kg N ha^{-1} was 67 kg kg^{-1}, whereas in the treatments where 160 kg and 240 kg N ha^{-1} were applied, it was 81 and 28 kg kg^{-1}, respectively.

Sharifi et al. (2007) revealed a positive correlation between total dry mass of potato plants and N accumulation in plants (r = 0.98) and a negative correlation between the total dry weight of plants and NUtE (r = –0.59). Research by Zebarth et al. (2004b) showed a dependence between NUE and NUtE due to a similar direction of those indices changing under the influence of plant nitrogen fertilization. This author's own investigations confirmed the occurrence of the same dependencies. Muurinen et al. (2007) and Rahimizadeh et al. (2010) demonstrated that, in cereal cultivation, NUE has a stronger relationship with NUpE than NUtE. The conducted experiments show that in potato cultivation, dependencies between NUE and NUpE and between NUE and NUtE are identical. Moreover, strict relationships were noted between NUpE and NRF, NUpE and NAE, NUtE and NPE, and NAE and NRF.

The effect of microbial preparations on plant yield and soil properties is not unanimously accepted. Cóndor-Golec et al. (2007) stated that experiments with positive research results were conducted mainly in Asian countries and that results were published in conference materials or in periodicals with low impact factors. Javaid and Shah (2010) revealed that application of EM preparation insignificantly or negatively influences the development and yield of wheat. Mayer et al. (2008) demonstrated a lack of significant effect of EM on plant yield and soil properties. Results of investigations also proved the insignificant or negative influence of microbial preparations on potato yield and shaping of nitrogen fertilization efficiency indices, particularly in plots receiving high N doses. Difficulties in obtaining significant results after application of microbial preparations result from the quantitative proportions. Microorganism biomass in the arable layer reaches several tons. For the microorganisms supplied to the soil in biopreparations to be able to compete with a huge mass of soil microorganisms, it would be necessary to use markedly larger amounts of biopreparations than recommended by manufacturers.

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