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The possibility of using sewage sludge for energy crop cultivation exemplified by reed canary grass and giant miscanthus

Abstract. Energy crops, on account of high biomass yields, have high nutrient requirements in relation to macroelements. Municipal sewage sludge can be a potential source of micronutrients for plants with high nutrient requirements. The use of macronutrients from sewage sludge by energy crops is an alternative form of nutrient recycling from organic waste. The aim of the research was to assess the content, uptake and use of N, P, K, Ca, Mg and Na from municipal sewage sludge by reed canary grass (*Phalaris arundinacea* L.) and giant miscanthus (*Miscanthus × giganteus* Greef et Deu). The effect of sewage sludge on the ratios between macroelements in the biomass of the tested plants was also assessed. The multi-year field experiment involved four levels of fertilization with sewage sludge at doses of 0, 10, 20, 40, 60 Mg DM·ha^{-1}. Due to the low potassium content in this waste, supplementary potassium fertilization (100 kg K·ha^{-1} in the form of 40% potassium salt (KCl)) was applied once on all plots. It was established that the increasing doses of sewage sludge had a considerable effect on the increase in the content and uptake of N, P, K, Ca, Mg and Na by the biomass of the tested energy crops. The research shows that, compared to giant miscanthus, reed canary grass had a higher macronutrient content. The largest amount of uptaken N, P, K, Ca and Mg was found in reed canary grass (at a dose of 40 Mg DM·ha^{-1}), whereas Na was detected in giant miscanthus (at a dose o 20 Mg DM·ha^{-1}). It was established that giant miscanthus, on account of its higher yielding, recovers macroelements from sewage sludge applied to soil at a dose of 10 Mg DM·ha^{-1} to the greatest extent. The increasing doses of sewage sludge considerably decreased the value of K:Mg, Ca:Mg, Ca:P ratios in miscanthus biomass yield. The applied doses of sewage sludge (40–60 Mg DM·ha^{-1}) increased the value of K:Ca, Ca:P, K:Na ratios in miscanthus biomass yield.

Keywords: reed canary grass, giant miscanthus, macroelements, phytoremediation

INTRODUCTION

Among the plant species introduced to cultivation and intended for the production of biomass for energy purposes, giant miscanthus takes a significant place (Saletnik et al. 2018). Production of bioenergy from solid biomass also includes production of biogas and liquid biofuels, hence the great interest in cultivation on arable land, mineral and organic fertilization of energy crops (Hu et al. 2018). Reed canary grass is another plant recommended for energy purposes (Dauber et al. 2010). Like fodder grass (owing to the rapid increase in biomass), reed canary grass responds very well to nitrogen fertilization, and it is resistant to drought, frost and shading (Lindvall et al. 2012).

Apart from organic pollutants and heavy metals, municipal sewage sludge constitutes a potential source of macroelements which can be recovered during the production of energy crop biomass (Antonkiewicz et al. 2018, Kicińska and Mamak 2017). Until now, in order to ensure high yields of biomass, rational mineral fertilization has generally been used. Attention is increasingly drawn to the recovery of macroelements from organic and mineral waste (Kicińska and Gruszecka-Kosowska 2016, Nahm and Morhart 2018, Szymańska et al. 2019). Thanks to this assumption, we can limit the use of mineral fertilizers in the context of retardation of natural resources. However, knowledge about the effect of large doses of sewage sludge on the environment of bioenergy plantations, particularly in the systems including long-term plantations as well as the effects of fertilization with macronutrients, is insufficient (Hu et al. 2018, Lindvall et al. 2015).

Owing to the long duration of plantation of these species and high biomass yield, attention was drawn to the possibility of using reed canary grass and mi-

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scanthus for the phytoremediation of macroelements from municipal sewage sludge. The aim of the research was to assess the content, uptake and use of N, P, K, Ca, Mg and Na from municipal sewage sludge by reed canary grass (*Phalaris arundinacea* L.) and giant miscanthus (*Miscanthus ×giganteus* Greef et Deu). The effect of increasing doses of sewage sludge on the ratios between macroelements in the biomass of the tested plants was also assessed in this study.

MATERIALS AND METHODS

Between 2008 and 2013, research was conducted on the effect of increasing doses of municipal sewage sludge on the content, uptake and utilization of macronutrients by reed canary grass and giant miscanthus on an area belonging to the municipal wastewater treatment plant in Janów Lubelski (50°43`17.7"N 22°22`08.0"E) located in south east Poland. This study is a continuation of the research on the extraction of heavy metals from sewage sludge by the above-mentioned plant species (Antonkiewicz et al. 2016).

Soil and municipal sewage sludge

The soil on which the experiment was set up was classified as clay loam (CL), (Table 1), (Polish Soil Classification 2011, Soil Survey Staff 2014). The soil had a slightly acid reaction. The content of available phosphorus and potassium was low, and the content of available magnesium was very low. Heavy metal content in the soil did not exceed permissible values when using municipal sewage sludge in agriculture and reclamation (Regulation 2016).

As organic waste with catalogue number 19 08 05 (Waste Catalogue 2014), the municipal sewage sludge was stabilized and hygienized before use. The field experiment used sewage sludge from the municipal wastewater treatment plant in Janów Lubelski. Municipal sewage sludge was applied once. It was mixed with the soil surface layer at the depth of 20 cm in late autumn of 2007. Because of the low potassium content in the sewage sludge, supplementary potassium fertilization (100 kg K·ha^{-1} in the form of 40% potassium salt (KCl)) was applied on all plots, (Table 1). Phosphorus fertilization was not applied in the field experiment since phosphorus content in the municipal sewage sludge satisfied the demand of energy crops for this nutrient. The determined content of Cr, Ni, Cu, Zn, Cd, Pb and Hg in the sewage sludge did not exceed permissible values when using municipal sewage sludge in reclamation (Table 1), (Regulation 2015).

TABLE 1. Selected physical and chemical properties of the soil before setting up the experiment and chemical composition of municipal sewage sludge used

Parameter	Unit	Content in the soil layer 0–20 cm	Content in the soil layer 20–40 cm	Content in sewage sludge
Fraction 2–0.05 mm	%	32	23	–
Fraction 0.05–0.002 mm		39	45	–
Fraction <0.002 mm		29	32	–
Dry matter		–	–	13.3
pH_{KCl}		6.29	6.44	6.04
Organic carbon	g·kg^{-1} DM	8.4	8.2	344.5
Available phosphorus (P)	mg·kg^{-1} DM	30.9	29.6	2.25
Available potassium (K)		91.3	60.6	Bdl*
Available magnesium (Mg)		27.6	24.6	0.28
Total nitrogen (N)	g·kg^{-1} DM	1.01	–	74.5
Total phosphorus (P)		0.35	–	12.5
Total potassium (K)		3.83	–	1.90
Total sodium (Na)		0.16	–	1.50
Total magnesium (Mg)		3.71	–	2.80
Total calcium (Ca)		8.95	–	2.90
Total chromium (Cr)	mg·kg^{-1} DM	9.66	9.89	25.4
Total nickel (Ni)		6.39	6.31	14.8
Total copper (Cu)		3.20	3.60	111
Total zinc (Zn)		31.97	31.00	1005
Total cadmium (Cd)		<0.27	<0.27	2.35
Total lead (Pb)		13.67	13.63	42.9

*Bdl – Below detection level

Experiment procedure and conditions

The two-factor field experiment was set up as a randomized block design on 14.4 m^2 plots, in three replicates. The dose of municipal sewage sludge was the first experimental factor. The scheme of the experiment comprised five treatments: 1 – control; 2 – 10 Mg DM; 3 – 20 Mg DM; 4 – 40 Mg DM and 5 – 60 Mg DM of municipal sewage sludge per ha. Two species of energy crops, namely reed canary grass (*Phalaris arundinacea* L.) of 'Bamse' cultivar and giant miscanthus (*Miscanthus ×giganteus* Greef et Deu), were the second experimental factor.

On 26 June 2008, 15 kg·ha^{-1} reed canary grass seeds were sown into rows 12 cm apart at a depth of 2 cm. Miscanthus rhizomes were planted on 22 April 2008 at 0.75×0.8 m spacing. The above-mentioned energy crops were harvested once in late autumn.

The determination of dry matter yield and the macroelement content and soil enzymatic activity

Every year (between 2008 and 2013), the energy crops were harvested in autumn, at the turn of October and November. After harvest, the plant material from each plot was dried at 70°C in a forced air circulation dryer, and then the yield of air-dry mass was determined. Samples of the analyzed crops were subjected to dry mineralization in a muffle furnace at 450°C (Ostrowska et al. 1991).

After microwave mineralization in a mixture of concentrated HCl and HNO_3 (3:1, *v/v*), close-to-total content of P, K, Na, Mg and Ca was determined in the air-dry soil samples and municipal sewage sludge (Ostrowska et al. 1991). After mineralization of the plant and soil material, the content of the above-mentioned elements was determined using an ICP-OES spectrometer (Jones and Case 1990). Total nitrogen content in the tested plants (plant material) and municipal sewage sludge was determined using the Kjeldahl distillation method (Ostrowska et al. 1991). Soil pH in 1 mol·dm^{-3} KCl was determined potentiometrically; organic carbon in the soil – by the Tiurin method; organic carbon in the sewage sludge was determined using a Vario MAX cube elemental macro analyzer (Elementar, Germany); dry matter content in the sewage sludge – by the dryer method; available P and K content was determined after Egner-Riehm method; and available Mg content was determined according to the Schachtschabel method (Ostrowska et al. 1991).

Analytical quality control

The ICP-OES Optima 7300 DV, atomic emission spectrometer from Perkin Elmer Company, was used to determine macroelements in plant and soil materials. Readings for each of the analyzed samples were conducted in three replications. For the data acquisition of the samples a quantitative analysis mode was used. The scanning of each single sample was repeated three times in order to obtain reasonably good results. During measurement, care was taken to avoid the memory effect and therefore a wash-out time of 0.5 min was used. The accuracy of the analytical methods was verified with the certified reference materials: CRM IAEA/V – 10 Hay (International Atomic Energy Agency), CRM – CD281 – Rey Grass (Institute for Reference Materials and Measurements), CRM023–050 – Trace Metals – Sandy Loam 7 (RT Corporation).

Calculations and statistical analysis of results

Owing to the cultivation of various plant species and the changeability of conditions in individual years, the content of N, P, K, Na, Mg and Ca in the total plant yield is presented as a weighted mean of the years 2008–2013. The annual uptake of the above-mentioned macroelements (U) was calculated as the product of dry matter yield (Y) and the content of macroelements (C), according to the formula:

$U = Y \cdot C.$

The balance of macroelements (B) was calculated from the difference between the amount of elements introduced (I) with the dose of sewage sludge and the amount of macronutrients taken up (U) with the plant yield, according to the formula:

$B = I - U.$

The simplified balance did not account for the input of macroelements with atmospheric precipitation, mineralization of organic matter, or the leaching of macroelements into the deeper layer of the soil profile. The phytoremediation of macroelements presented in the balance is the percentage uptake of macroelements by plants in relation to the amounts introduced into the soil along with the municipal sewage sludge. This study also presents quantitative ratios between the studied nutrients in the energy crop biomass. Mass ratios for K:Na, Ca:Mg and Ca:P as well as equivalent ratios for K:(Ca+Mg), K:Mg and K:Ca were calculated.

The statistical analysis of the research results was conducted using a Microsoft Office Excel 2003 spreadsheet and Statistica package version 10 PL. The statistical evaluation of result variability was carried out using the two-factor analysis of variance. The significance of differences between mean values was verified using t-Tukey's test at the significance level $\alpha \leq 0.05$. For selected parameters (ratios), the value of Pearson's linear correlation coefficient (r) was computed, at a significance level of $\alpha \leq 0.05$. The maximum 5% dispersion between measurements in chemical analysis was adopted.

RESULTS

Yield of plants

An earlier publication presented the amount of reed canary grass and giant miscanthus dry matter yield in particular years of vegetation (Antonkiewicz et al. 2016). This study presents the mean yield of energy crops from the years 2008–2013. Depending on the dose of sewage sludge, the mean dry matter yield of reed canary grass ranged from 5.3 to 13.4 Mg DM·ha^{-1}, whereas the mean dry matter yield of giant miscanthus varied from 11.3 to 17.3 Mg DM·ha^{-1} (Fig.). The lowest dry matter yield was obtained in the control treatment (without fertilization), whereas the increasing doses of sewage sludge significantly increased the yield of the tested plants. The conducted research shows that the highest yield-forming effect for reed canary grass was obtained in the treatment where 40 Mg·ha^{-1} sewage sludge DM had been applied, and for giant miscanthus – 20 Mg·ha^{1} sewage sludge DM.

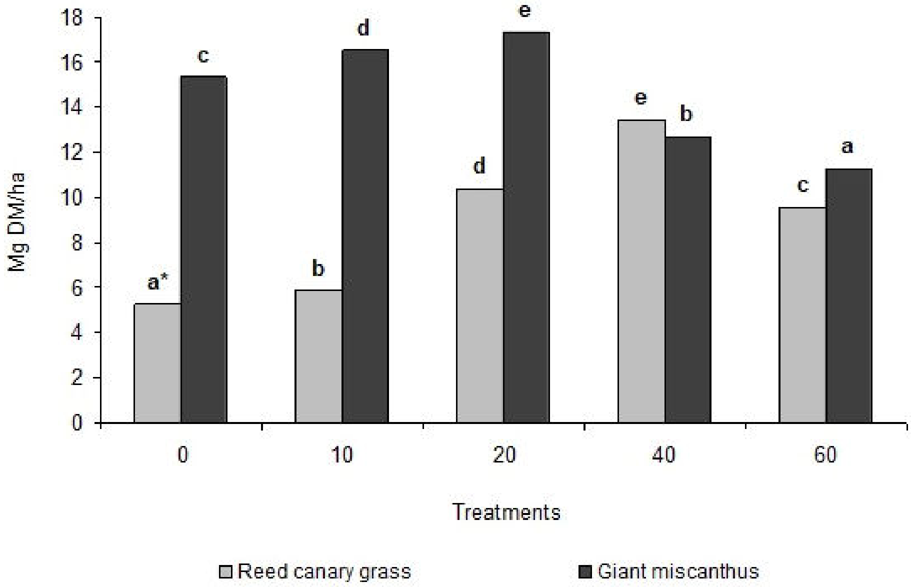

FIGURE. The average yield of the energy crops (2008–2013). * The different letters are statistically significant different at α=0.05 according to HSD Tukey's test

Macroelement content

The applied sewage sludge constituted a potential source of macronutrients for the tested energy crops. It was established that the total content of the above-mentioned elements in this waste was over 72.7 and 34.7, which is 8.3 times more than the soil surface layer (Table 1). The soil on which the field experiment was set up had a higher total content of K, Mg and Ca compared to the sewage sludge. The content of total forms of the above-mentioned elements in the soil was over 2.0 and 1.3, which is 3.1 times more than their content in sewage sludge.

The lowest macroelement content in the energy crops was recorded in the control treatment. Application of increasing doses of sewage sludge to soil (in the amount of 10–60 Mg DM·ha^{-1}) significantly increased the content of N, P, K, Na, Ca and Mg in the analyzed energy crops (Table 2). At the highest dose of sewage sludge (60 Mg DM·ha^{-1}), the amount of N, P, K, Na, Ca and Mg in reed canary grass was over 51, 53, 56, 60, 69, 71% respectively higher than the control treatment. Giant miscanthus contained over 147, 105, 45, 39, 33, 105% respectively more P, K, Na, Ca and Mg than the control treatment. The author's own research showed that the increasing doses of sewage sludge differentiated the content of macronutrients in the analyzed energy crops. Compared to giant miscanthus, reed canary grass contained considerably more of the studied macronutrients, regardless of fertilizer combination. At the same time it was established that at the highest dose of sewage sludge, the content of Ca and Mg increased the most in reed canary grass, and N content increased the most in giant miscanthus.

The analysis of the Pearson's linear correlation (r) indicated strong relationships between the amount of macronutrients (N, P, K, Na, Ca, Mg) introduced with the dose of sewage sludge and the content of these elements in the tested species of energy crops (r=0.41–0.86). The analysis of correlation also showed a significant relationship between the mean plant yield and the content of N, P, K and Mg in the tested plant species (r=0.53–0.63). No significant correlations between the mean yield and the content of Na and Ca in the energy crops were recorded. The calculated correlations are indicative of a significant effect of sewage sludge on the chemical composition of biomass of e analyzed plant species.

TABLE 2. Weighted average of macroelements content in energy crops (g·kg^{-1} DM)

Treatments	N	P	K	Na	Ca	Mg
Sludge dose (Mg DM·ha^{-1})	Reed canary grass					
0	10.9	0.71	4.3	0.26	1.27	0.67
10	13.2	0.78	4.8	0.29	1.45	0.75
20	14.4	0.83	5.1	0.33	1.58	0.82
40	14.9	0.90	5.8	0.36	1.80	0.92
60	16.4	1.08	6.8	0.42	2.14	1.14
Mean	13.9	0.86	5.4	0.33	1.65	0.86
CV (%)*	14.2	16.1	17.4	18.4	19.5	20.5
Sludge dose (Mg DM·ha^{-1})	Giant miscanthus					
0	5.8	0.30	2.4	0.26	1.10	0.24
10	7.5	0.33	2.7	0.28	1.17	0.27
20	8.7	0.37	2.9	0.31	1.28	0.30
40	12.8	0.45	3.3	0.33	1.33	0.35
60	14.4	0.62	3.5	0.36	1.43	0.50
Mean	9.8	0.42	3.0	0.31	1.26	0.33
CV (%)*	34.4	29.0	14.3	12.2	10.5	28.6
Sludge dose (Mg DM·ha^{-1})	Mean for dose of the sewage sludge					
0	8.3	0.51	3.4	0.26	1.17	0.45
10	10.3	0.55	3.7	0.29	1.31	0.51
20	11.5	0.60	4.0	0.32	1.43	0.56
40	13.8	0.67	4.5	0.35	1.57	0.63
60	15.4	0.85	5.1	0.39	1.79	0.82
LSD for dose**	0.4	0.03	0.2	0.02	0.05	0.04
LSD for species	0.6	0.04	0.4	0.03	0.08	0.06
LSD for interaction	0.9	0.06	0.5	0.04	0.12	0.08

* CV – Variability Coefficient; **LSD – Least Significant Differences

TABLE 3. Value of concentration index (CI) in energy crops

Treatments	N	P	K	Na	Ca	Mg
Sludge dose (Mg DM·ha^{-1})	Reed canary grass					
0	–	–	–	–	–	–
10	1.21	1.09	1.11	1.13	1.14	1.13
20	1.32	1.17	1.19	1.28	1.24	1.23
40	1.36	1.27	1.33	1.40	1.42	1.37
60	1.51	1.53	1.56	1.60	1.69	1.71
Mean	1.35	1.26	1.30	1.35	1.37	1.36
Sludge dose (Mg DM·ha^{-1})	Giant miscanthus					
0	–	–	–	–	–	–
10	1.29	1.10	1.10	1.11	1.09	1.11
20	1.50	1.22	1.22	1.22	1.19	1.24
40	2.21	1.50	1.36	1.29	1.24	1.44
60	2.48	2.06	1.45	1.39	1.34	2.05
Mean	1.87	1.47	1.28	1.25	1.22	1.46

Concentration index (CI)

The concentration index is defined as the ratio of the content of a given element in a plant cultivated on a fertilization plot (with the addition of sewage sludge) to the content of the nutrient in a plant cultivated under control conditions (without fertilization). Based on the value of the concentration index (CI), we can determine the 'potential' of a plant to accumulate the nutrient in biomass. A higher value of CI indicates that a given nutrient in a plant has been moving more intensively in fertilization treatments compared to the control treatment. In addition, this index tells us that in certain conditions a particular nutrient is taken up by a plant to a higher degree compared to other nutrients or plants. A higher value of CI indicates that plants may grow more intensely, and that they have sufficient amounts of all nutrients.

Table 3 shows values of the concentration index (CI) for individual elements and plant species. The values indicate that giant miscanthus took up N, P and Mg from sewage sludge more intensely than reed canary grass (cultivated in the same conditions). Reed canary grass took up Na and Ca from sewage sludge more intensely compared to giant miscanthus.

Macroelement uptake by plants

Table 4 shows the macronutrient uptake by the energy crops, as a sum of the entire research period (2008–2013). The lowest amounts of macronutrients taken up by the plants were recorded in the control

TABLE 4. Total macroelements uptake by energy plants (kg·ha^{-1})

Treatments	N	P	K	Na	Ca	Mg
Sludge dose (Mg DM·ha^{-1})	Reed canary grass					
0	345	22.4	137	8.2	40.2	21.1
10	460	27.1	168	10.3	50.6	26.4
20	895	51.5	320	20.7	98.1	51.2
40	1193	72.0	463	29.2	144.7	73.6
60	947	62.4	389	23.9	123.4	65.6
Mean	768	47.1	295	18.5	91.4	47.6
CV (%)*	42.9	43.0	44.3	45.5	46.2	45.9
Sludge dose (Mg DM·ha^{-1})	Giant miscanthus					
0	531	27.8	222	23.6	98.6	22.2
10	743	33.0	264	28.3	116.4	26.6
20	902	38.1	306	32.5	132.7	31.0
40	972	34.4	250	25.3	101.0	26.3
60	973	42.1	237	24.2	96.9	33.5
Mean	824	35.1	256	26.8	109.1	27.9
CV (%)*	21.7	14.8	12.3	13.1	13.4	15.4
Sludge dose (Mg DM·ha^{-1})	Mean for dose of the sewage sludge					
0	438	25.1	180	15.9	69.4	21.7
10	601	30.1	216	19.3	83.5	26.5
20	899	44.8	313	26.6	115.4	41.1
40	1082	53.2	356	27.2	122.8	49.9
60	960	52.2	313	24.1	110.2	49.6
LSD for dose**	31	2.0	13	1.0	4.0	2.5
LSD for species	49	3.2	20	1.5	6.4	3.9
LSD for interaction	70	4.5	29	2.2	9.0	5.5

* CV – Variability Coefficient, **LSD – Least Significant Differences

treatment, where no fertilization was applied. This resulted, among other things, from the lowest yield (Figure) and low content of these nutrients in the plant biomass (Table 2). Application of increasing doses of sewage sludge significantly increased the amount of macronutrients taken up by the energy crops. The largest quantities of macronutrients taken up with the yield of reed canary grass were obtained at a dose of 40 Mg DM·ha^{-1}. The uptake of N, P, K, Na, Ca and Mg by reed canary grass was, respectively, over 245, 220, 237, 255, 260 and 248% higher compared to the control treatment. The largest amounts of N, P and Mg taken up with the miscanthus yield were obtained in reed canary grass at a dose of 60 Mg DM·ha^{-1}, whereas the largest amounts of K, Na and Ca – at a dose of 20 Mg DM·ha^{-1}. The uptake of the above-mentioned macronutrients was over 83, 51, 51, 37, 37, 34% respectively higher than the control treatment. When comparing the percent increase in the uptake of macronutrients, it was established that reed canary grass responded with more intense (220–260%) uptake of macronutrients compared to giant miscanthus (34–83%). When also comparing the quantitative uptake of macronutrients, depending on treatment, it was established that reed canary grass took up more N, P, K, Ca and Mg than giant miscanthus. Compared to reed canary grass, the only element giant miscanthus took up more was Na.

Despite the decrease in yielding of miscanthus (at a dose of 40 Mg·ha^{-1} sewage sludge DM) and reed canary grass (at a dose of 60 Mg·ha^{-1} sewage sludge DM) (Fig.), the amounts of uptaken macronutrients were higher compared to the control. On one hand, this was a result of the increased concentration of these elements in the plant biomass. On the other hand, it was caused by differences in plant yielding (Table 4).

Significant correlations were found between the amount of macronutrients introduced with doses of sewage sludge and the uptake of these nutrients by the plants (r=0.39–0.77). The linear correlation analysis also showed strong relationships between the mean yield of the tested species and the uptake of N, K, Na and Ca by these plants. Significant relationships were also found between the content of macronutrients in the plants and the uptake of these nutrients (r=0.39–0.78).

Simplified balance and phytoremediation of macroelements

The balance and phytoremediation of macronutrients from municipal sewage sludge allowed for the assessment of the amount (doses) of this waste that can be introduced into the environment in fertilization aspect. The results of the balance of macronutrients was determined by the amount of nutrients introduced with sewage sludge and the total uptake of macronutrients with the yield of the tested species (Table 5). In the treatments not fertilized with sewage sludge (control), the balance was always negative. The increasing doses of sewage sludge (10–60 Mg DM·ha^{-1})

TABLE 5. Simplified balance of macroelements after six years of research

Treatments	Introduced kg·ha^{-1}	Uptake	Balance	Recovery	Uptake	Balance	Recovery
				%	kg·ha^{-1}		%
		Reed canary grass			Giant miscanthus		
Sludge dose (Mg DM·ha^{-1})	N						
0	0	345	-345	0	531	-531	0
10	745	460	285	62	743	2	100
20	1490	895	595	60	902	588	61
40	2980	1193	1787	40	972	2008	33
60	4470	947	3523	21	973	3497	22
Sludge dose (Mg DM·ha^{-1})	P						
0	0	22	-22	0	28	-28	0
10	125	27	98	22	33	92	26
20	250	52	198	21	38	212	15
40	500	72	428	14	34	466	7
60	750	62	688	8	42	708	6
Sludge dose (Mg DM·ha^{-1})	K						
0	0	137	-137	0	222	-222	0
10	119	168	-49	141	264	-145	222
20	138	320	-182	232	306	-168	222
40	176	463	-287	263	250	-74	142
60	214	389	-175	182	237	-23	111
Sludge dose (Mg DM·ha^{-1})	Na						
0	0	8	-8	0	24	-24	0
10	15	10	5	68	28	-13	188
20	30	21	9	69	32	-2	108
40	60	29	31	49	25	35	42
60	90	24	66	27	24	66	27
Sludge dose (Mg DM·ha^{-1})	Ca						
0	0	40	-40	0	99	-99	0
10	28	51	-22	175	116	-87	401
20	56	98	-40	169	133	-75	229
40	112	145	-29	125	101	15	87
60	168	123	51	71	97	77	56
Sludge dose (Mg DM·ha^{-1})	Mg						
0	0	21	-21	0	22	-22	0
10	29	26	2	94	27	1	95
20	58	51	5	91	31	25	55
40	116	74	38	66	26	86	24
60	174	66	102	39	34	134	20

led to a positive value of N, P and Mg balance in the tested plant species. The positive value of N, P and Mg balance resulted mainly from the larger amounts of these nutrients introduced with sewage sludge than their uptake by plants. For both tested plant species, a positive Ca balance was recorded in the treatment with the highest dose of sewage sludge (60 Mg DM·ha^{-1}). In the case of Na, the increasing doses of sewage sludge also led to a positive value of the balance only for reed canary grass. A positive Na balance for giant miscanthus was recorded in the treatments where the highest doses of sewage sludge, i.e. 40 and 60 Mg DM·ha^{-1}, were applied. The negative K balance in the fertilization treatments (10–60 Mg DM·ha^{-1}) resulted from the higher uptake of this element by the tested plant species compared to the amounts introduced with the dose of sewage sludge.

The highest percent of phytoremediation of N, P, K, Na, Ca and Mg from sewage sludge by giant miscanthus was calculated in the treatment where 10 Mg DM·ha^{-1} of this organic waste was applied. The increasing doses of sewage sludge (20–60 Mg DM·ha^{-1}) decreased the phytoremediation of these macronutrients. This resulted mainly from the amount of macronutrients introduced with the dose of sewage sludge, the amount of yield, and from the amount of uptake of these nutrients by miscanthus. In the case of reed canary grass, the highest phytoremediation of N, P, Ca and Mg was also recorded in the treatment where the lowest doses of sewage sludge (10 Mg DM·ha^{-1}) were applied. Na and K were used the most in the treatments where the applied doses of sewage sludge were 20 and 40 Mg DM·ha^{-1} respectively. When assessing the tested energy crops species, it was established that giant miscanthus used (phytoremediation) N, P, Na, Ca and Mg to a higher degree compared to reed canary grass. Potassium (K) was used by reed canary grass to a higher degree compared to giant miscanthus.

It was established that among the evaluated macronutrients, phytoremediation of K, Na and Ca was higher than the amount introduced to soil with sewage sludge. This confirms that the abovementioned elements were taken up not only from the sewage sludge but also from soil resources. When comparing the percent of phytoremediation of macronutrients by the tested species (regardless of the fertilization treatment), a series of diminishing values can be established so that Ca > K > Na > N > Mg > P. The series suggests that the tested plants (regardless of the treatment) recovered Ca to the greatest degree, while P – to the smallest.

Soil enzymatic activity

Application of sewage sludge to the soil introduced considerable amounts of biogenes, organic colloids and soil microorganisms that release soil enzymes which affect plants. In the first part of the research (Antonkiewicz et al. 2016), a high level of activity of the studied enzymes was recorded. This confirms the efficiency of using sewage sludge as an organic fertilizer in cultivation of energy crops, as well as the positive effect of this fertilization on soil microorganisms and on soil biological activity. This research revealed significant correlations between soil enzymatic activity and the amount of macroelements introduced with the dose of sewage sludge (r=0.85–0.97); the content of macroelements in energy crops (r=0.37–0.67); macroelement uptake by energy crops (r=0.36–0.75).

Ratios between elements

Table 6 presents ratios between elements present in the energy crop biomass. A small range of variability of ratios between macroelements in reed canary grass and giant miscanthus biomass was recorded. It needs to be stated that biomass of the tested plants, regardless of the treatment (the dose of sewage sludge), was characterized by constant ratios between these elements.

The increasing doses of sewage sludge caused a systematic reduction in the value of K:Na, K:Mg and K:Ca ratio in reed canary grass biomass compared to the control treatment. A significant reduction in ratio values in reed canary grass biomass was recorded only in the case of K:Ca ratio, at the highest doses of sewage sludge (40 and 60 Mg DM·ha^{-1}). The increasing doses of sewage sludge (10–60 Mg DM·ha^{-1}) significantly increased the value of Ca:P ratio in reed canary grass biomass compared to the control treatment. Compared to the control, the applied doses of sewage sludge did not change the values of Ca:Mg and K:(Ca+Mg) ratios in reed canary grass biomass.

Giant miscanthus, under the influence of sewage sludge doses in the amount of 40 and 60 Mg DM·ha^{-1}, responded significantly with an increase in values of K:Na and K:Ca ratios in the biomass compared to the control. The applied above-mentioned doses of sewage sludge had a great effect on the decrease in values of K:Mg, Ca:Mg and Ca:P ratios in miscanthus biomass. As in the case of reed canary grass, increasing doses of sewage sludge did not significantly change the value of K:(Ca+Mg) ratio in miscanthus biomass compared to the control. The analysis of Pearson's linear correlation showed a negative relationship between P content and Ca:P ratio in the plant biomass (r=-0.89). Potassium content in the plant biomass was positively correlated with K:Na, K(Ca+Mg) and K:Ca ratios (r=0.40–0.84), and negatively correlated with K:Mg ratio (r=-0.81). Magnesium content in the energy crops was negatively correlated with K:Mg and Ca:Mg ratios (r=-0.90–0.91). The research also revealed that Ca content in the plant biomass determined the value of K:Ca, Ca:Mg, Ca:P ratios. Correlation coefficient for these ratios was 0.50, -0.67, -0.61 respectively. Significant correlations were also shown between Na uptake and K:Na ratio in the plant biomass. The uptake

TABLE 6. Relationships between elements in energy crops

Treatments	K:Na	Ca:Mg	Ca:P	K:(Ca+Mg)	K:Mg	K:Ca
Sludge dose (Mg DM··ha^{-1})	Reed canary grass					
0	16.7	1.9	1.8	0.9	2.0	1.8
10	16.4	1.9	1.9	0.9	2.0	1.7
20	15.5	1.9	1.9	0.9	1.9	1.7
40	15.8	2.0	2.0	0.9	2.0	1.6
60	16.3	1.9	2.0	0.9	1.9	1.6
Mean	16.1	1.9	1.9	0.9	2.0	1.7
CV (%)*	3.7	7.8	6.9	7.5	8.8	8.1
Sludge dose (Mg DM··ha^{-1})	Giant miscanthus					
0	9.4	4.4	3.5	0.8	3.1	1.2
10	9.3	4.4	3.5	0.8	3.1	1.2
20	9.4	4.3	3.5	0.9	3.1	1.2
40	9.9	3.8	2.9	0.9	2.9	1.3
60	9.8	2.9	2.3	0.8	2.2	1.3
Mean	9.6	4.0	3.2	0.8	2.9	1.2
CV (%)*	4.9	15.3	16.1	4.4	12.9	5.0
Sludge dose (Mg DM··ha^{-1})	Mean for dose of the sewage sludge					
0	13.0	3.2	2.7	0.9	2.6	1.5
10	12.9	3.2	2.7	0.9	2.5	1.4
20	12.5	3.1	2.7	0.9	2.5	1.4
40	12.9	2.9	2.5	0.9	2.5	1.5
60	13.0	2.4	2.1	0.8	2.0	1.4
LSD for dose**	0.4	0.1	0.1	0.1	0.1	0.1
LSD for species	0.6	0.2	0.1	0.1	0.2	0.1
LSD for interaction	0.8	0.3	0.2	0.1	0.3	0.2

* CV – Variability Coefficient,

**LSD – Least Significant Differences

of Mg by the energy crops had a considerable effect on K:Mg and Ca:Mg ratios in the biomass of these plants. The uptake of Ca by the plants determined the value of K:Ca and Ca:Mg ratios.

DISCUSSION

Yield of the tested plants

Earlier studies showed that the increasing doses of sewage sludge significantly increased the yield of reed canary grass and giant miscanthus compared to the control (Figure), (Antonkiewicz et al. 2016). It was also shown that giant miscanthus had a higher yield than reed canary grass. Other authors' studies confirm that giant miscanthus has a substantial yield-forming potential and responds well to mineral fertilization (Ozdemir et al. 2018, Saletnik et al. 2018). Other studies (Butkute et al. 2011) also confirm that reed canary grass responds very well with its yield to mineral fertilization, including nitrogen fertilization. The study by Kharytonov et al. (2019) confirms that energy crops, including miscanthus, also respond well to fertilization with organic waste.

Macronutrient content

Apart from heavy metals, municipal sewage sludge constitutes a potential source of macronutrients for crops, particularly for energy crops with high nutrient requirements (Antonkiewicz et al. 2018, Kicińska and Mamak 2017, Ozdemir et al. 2018). The study by Ozdemir et al. (2018) confirms that sewage sludge applied under energy crops caused an increase in the content of macronutrients in the plant biomass. Other authors' studies indicate that arable soils contain more K, Ca and Mg compared to municipal sewage sludge (Ozdemir et al. 2018). Total forms of K, Ca and Mg are found in soil minerals which are not readily available to plants (Wojciechowska et al. 2019). Only available forms of these nutrients can be taken up by plants (Tkaczyk et al. 2017, Symanowicz et al. 2018). The higher macronutrient content in reed canary grass recorded in the authors' own research presumably resulted from the lower yield, and thereby from a higher 'concentration' of nutrients in the plant biomass. Other authors' studies confirm that plants with higher yields are characterized by the 'dilution effect', hence the lower content of the analyzed elements in the plant biomass can be explained (Antonkiewicz et al. 2018, Pogrzeba et al. 2018, Witkowicz et al. 2015). The value of the concentration index (CI) indicates that reed canary grass took up Na and Ca from sewage sludge more intensely. This suggests that the species can be intended for remediation, removal of salt compounds from saline soils. The study by Krol et al. (2019) confirms that reed canary grass and giant miscanthus tolerate cultivation on soils with neutral and alkaline reaction and on saline soils well.

Macronutrient uptake

Macronutrient uptake by energy crops is determined by reaction and availability of nutrients (Watros et al. 2019, Symanowicz and Kalembasa. 2019). Our research revealed that the lower the dose of sewage sludge, the lower the uptake of macronutrients with the yield of reed canary grass and giant miscanthus biomass. The lower amount of macronutrients uptaken results from the amount of yield and the 'dilution effect' of these nutrients in the plant biomass, which finds confirmation in other studies (Antonkiewicz et al. 2018, Berglund et al. 2019, Biel et al. 2017). The study by Berglund et al. (2019) also confirms that reed canary grass utilizes macronutrients well and, compared to other species of grasses, it takes up more of them with the yield compared to the amounts introduced with fertilizers.

Balance and utilization

Municipal sewage sludge is recommended, among other things, in reclamation of post-industrial areas, in management of marginal lands, in biomass production for energy purposes (Schröder et al. 2018, Kosa and Kicińska 2016). The use of sewage sludge is associated with the introduction of large amounts of macronutrients which can be a potential source for energy crops (Huygens and Saveyn 2018). An important part of rational use of sewage sludge is optimal utilization of macronutrients from this waste introduced to soil (Huygens and Saveyn 2018; Saletnik et al. 2018). The research shows that, compared to the multiflora rose and the Virginia fanpetals, reed canary grass and giant miscanthus utilized macronutrients more (Antonkiewicz et al. 2018). The higher utilization of Na, K and Ca by the plants indicates that reed canary grass and giant miscanthus can be used for remediation of saline soils, which finds confirmation in other studies (Loser and Zehnsdorf 2002).

Soil enzymes

Scientific literature suggests that the use of sewage sludge in cultivation of energy crops increases soil biological activity (Ruf et al. 2018). The increased soil enzymatic activity confirms that, as a result of mineralization of organic matter, sewage sludge makes macronutrients available to plants (Joniec 2018). The obtained results of the authors' own research have been confirmed by other authors (Symanowicz et al. 2018).

Proportions between nutrients

Interrelationships between elements in the plant biomass constitute an important qualitative aspect in terms of using them for fodder purposes (Biel et al. 2017, Klikocka et al. 2018, Witkowicz et al. 2015). The author's own research showed that the proportions between macronutrients in the tested energy crops underwent slight changes. Scientific literature suggests that, compared to other fodder plants and grasses, reed canary grass is characterized by poor biomass quality (Butkute et al. 2011, Cieślik et al. 2017). The tested energy crops can also be a fodder raw material. That is why the obtained chemical composition of plant biomass was evaluated based on criteria of the feed nutrient value, according to which the optimal ratios of Ca:P, Ca:Mg, K:Na, K:(Ca+Mg), K:Mg, K:Ca should amount to 2:1, 2–3:1, 10:1, 1.6–2.2:1, 6:1, 2:1, respectively (Mackowiak et al. 2011, Poutanen et al. 2014). When evaluating the biomass chemical composition, it was established that values of Ca:P, Ca:Mg, K:(Ca+Mg), K:Mg and K:Ca ratios in the above-ground parts of reed canary grass and giant miscanthus were below optimal values. Only the value of K:Na ratio in reed canary grass biomass was above optimal values. The research shows that biomass of energy crops, produced on soil fertilized with sewage sludge, is characterized by constant ratios between elements. Moreover, ratios between elements are of significant importance in the quality of biomass intended also for energy purposes (Tonn et al. 2012, Kołodziej et al. 2016).

CONCLUSIONS

1. The increasing doses of sewage sludge increased energy crop yields. Giant miscanthus had a higher yield potential than reed canary grass.
2. The sewage sludge caused a considerable increase in the content of macronutrients in the biomass of energy crops. Compared to giant miscanthus, reed canary grass accumulated more N, P, K, Na, Ca and Mg.
3. Compared to giant miscanthus, reed canary grass took up more N, P, K, Ca and Mg. The only element giant miscanthus took up more compared to reed canary grass was Na.
4. The highest percent of phytoremediation of macronutrients by the tested plant species concerned Ca, followed by (in order) K > Na > N > Mg > P.
5. A small range of variability of ratios between macroelements in the energy crop biomass was recorded. Values of Ca:P, Ca:Mg, K:(Ca+Mg), K:Mg and K:Ca ratios in the above-ground parts of reed canary grass and giant miscanthus were below optimal values.
6. Based on the amount of macronutrient uptake, reed canary grass can be regarded as a potential plant for phytoremediation of municipal sewage sludge macronutrients.

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Możliwości wykorzystania osadów ściekowych w uprawie roślin energetycznych na przykładzie mozgi trzcinowatej i miskantusa olbrzymiego

Streszczenie. Rośliny energetyczne, z racji wysokich plonów biomasy, cechują się dużymi wymaganiami pokarmowymi w stosunku do makroelementów. Potencjalnym źródłem makroskładników dla roślin o dużych wymaganiach pokarmowych, mogą być komunalne osady ściekowe. Wykorzystanie makroskładników z osadów ściekowych przez rośliny energetyczne stanowi alternatywną formę recyklingu składników pokarmowych z odpadów organicznych. Celem badań była ocena zawartości, pobrania i wykorzystania N, P, K, Ca, Mg i Na z komunalnych osadów ściekowych przez mozgę trzcinowatą (*Phalaris arundinacea* L.) i miskanta olbrzymiego (*Miscanthus*×*giganteus* Greef et Deu). Dokonano również oceny wpływu osadów ściekowych na proporcje między makroelementami w biomasie testowanych roślin. W wieloletnim doświadczeniu polowym zastosowano cztery poziomy nawożenia osadem ściekowym w dawkach: 0, 10, 20, 40, 60 Mg DM·ha^{-1}. Ze względu na niską zawartość potasu w tym odpadzie na wszystkich poletkach zastosowano jednorazowo uzupełniające nawożenie potasowe w ilości 100 kg K·ha^{-1}, w postaci 40% soli potasowej (KCl). Stwierdzono, że wzrastające dawki osadu ściekowego istotnie wpłynęły na zwiększenie zawartości i pobrania N, P, K, Ca, Mg i Na przez biomasę testowanych roślin energetycznych. Z badań wynika, że mozga trzcinowata cechowała się większą zawartością makroskładników w porównaniu do miskanta olbrzymiego. Największą ilość pobranego N, P, K, Ca i Mg stwierdzono w mozdze trzcinowatej, przy dawce 40 Mg DM·ha^{-1}, natomiast Na w miskantusie olbrzymim, przy dawce 20 Mg DM·ha^{-1}. Stwierdzono, że miskantus olbrzymi, z racji większego plonowania, w największym procencie odzyskuje makroelementy z osadu ściekowego zaaplikowanego do gleby w dawce 10 Mg DM·ha^{-1}. Wzrastające dawki osadu ściekowego wpłynęły istotnie na obniżenie wartości proporcji K:Mg, Ca:Mg, Ca:P w plonie biomasy miskantusa. Zastosowane dawki osadów ściekowych w ilości 40–60 Mg DM·ha^{-1} wpłynęły na zwiększenie wartości proporcji K:Ca, Ca:P, K:Na w plonie biomasy miskantusa.

Key words: mozga trzcinowata, miskant olbrzymi, makroelementy, fitoodzysk