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The effect of municipal sewage sludge on the content, use and mass ratios of some elements in spring barley biomass

Abstract: Municipal sewage sludge contains considerable amounts of macro and microelements essential for plant nutrition. With decreasing use of natural and organic fertilizers, there is a need to search for alternative sources of organic matter (which is a substrate for humus reproduction). In a field experiment carried out on heavy soil with neutral reaction, the effect of single application of municipal sewage sludge in a dose of 5.34 Mg·ha⁻¹ DM was compared to an equivalent dose of mineral fertilizers. The test plant was spring barley. After application of municipal sewage sludge, slight positive changes in the chemical properties of the soil were observed. The sewage sludge increased the yield of spring barley grain and straw by, respectively, 14 and 13% in relation to treatment with mineral fertilization. Spring barley fertilized with sewage sludge contained more elements than barley grown only on mineral fertilizers. It was shown that application of municipal sewage sludge to the soil had a significant effect on increase in nutrient uptake by spring barley. Fe was taken up in the highest amount, followed by Al and Mn, and Co was taken up in the smallest amounts. Utilization of Fe, Mn, Co and Al from sewage sludge by spring barley was at 6.0, 4.7, 0.7 and 0.7%, respectively of the amount applied to the soil with this waste. The mass ratios (Fe:Mn, Fe:Al, Mn:Co) analyzed in spring barley biomass were much wider in straw than in grain. In terms of grain feed value, Fe:Mn ratio in grain and straw was greater than optimum.

Keywords: spring barley, yields, sewage sludge, uptake, Fe, Mn, Co, Al

INTRODUCTION

With constantly increasing amounts of generated municipal sewage sludge, the problem of its management is growing (Environment 2016). Sewage sludge can be managed environmentally or used as an alternative source of energy (Fytyli and Zabaniotou 2008, He et al. 2013). Total amount of sewage sludge generated in Poland in 2015 was 568 thousand Mg dry matter, out of which approximately 107.5 thousand Mg DM was used in agriculture. Apart from farming, municipal sewage sludge was used in reclamation in the amount of 19.2 thousand Mg DM, whereas 40.5 thousand Mg DM was disposed (Environment 2016).

High abundance in nutrients such as N, P, Mg, Ca and in microelements, as well as a high organic matter content, speak in favor of environmental (including agricultural) use of municipal sewage sludge (Nabulo et al. 2011, Shaheen et al. 2014, Ahmed et al. 2010, Wiczorek 2013). At a decreasing amount of natural and organic fertilizers used (Statistical Yearbook of Agriculture 2015), high amounts of organic matter (which is substrate for reproduction of humus) can be intro-

duced to soil with sewage sludge. The use of municipal sewage sludge in agriculture is considered to be rational owing to the assurance of circulation of macro- and microelements and organic matter in agroecosystems (Gondek et al. 2012, Kelessidis and Stasinakis 2012).

Municipal sewage sludge from rural sewage treatment plants that receive mainly domestic wastewater generally does not contain excessive amounts of heavy metals (Werle and Wilk 2010). This sludge is rich in nutrients necessary for plants, and that is why it is recommended to use it in agriculture for fertilizing purposes (Bauman-Kaszubska and Sikorski 2008, Alvarenga et al. 2015, Kępka et al. 2016).

The aim of the undertaken research was to assess the effect of municipal sewage sludge on the content, uptake and use of Fe, Mn, Co and Al by spring barley. Fertilization of spring barley with municipal sewage sludge increases not only the amount of grain and straw yield, but also the content of elements in biomass, and some of them are particularly valuable owing to the nutritional and feed use.

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MATERIALS AND METHODOLOGY OF THE RESEARCH

The research on agricultural use of municipal sewage sludge was carried out in a field experiment on two production fields (each with a surface of 1 ha) in the commune of Iwanowice in the Małopolska province. This paper is continuation of research on the effect of municipal sewage sludge on chemical composition of spring barley (Kępka et al. 2016).

Soil and municipal sewage sludge

Basic chemical properties of the soil and municipal sewage sludge used in the experiment are provided in Table 1. The soil on which the field experiment was set up was classified into brown soils with granulometric composition of silt loam (13% sand, 53% silt, 34% clay (Polish Soil Classification 2011)). The soil reaction was neutral, and the content of available forms of P, K and Mg was very low. Heavy metal content in the soil did not exceed acceptable values allowing for agricultural use of municipal sewage sludge (Regulation 2015).

Municipal sewage sludge, as organic waste with catalogue number 190805 (Catalogue of wastes 2014), came from the sewage treatment plant in the commune of Iwanowice. The sludge was stabilized and hygienized with burnt lime. The sludge was applied once on the field surface and plowed at a depth of 25 cm.

TABLE 1. Physicochemical properties of soil and municipal sewage sludge

Parameter	Unit	Soil	Sewage sludge
Fraction 2–0.05 mm	%	13	–
Fraction 0.05–0.002 mm		53	–
Fraction <0.002 mm		34	–
Dry matter		–	22.2
pH _(H2O)		7.15	9.14
pH _(KCl)		6.95	–
Organic matter	g·kg ⁻¹ DM	20.9	554
Fe	mg·kg ⁻¹ DM	11225	1852
Mn		569	458
Co		5.78	8.23
Al		8562	5345
N total	g·kg ⁻¹ DM	1.11	22.3
P total		0.12	3.7
K total		6.33	2.5
Na total		2.31	1.1
Ca total		16.53	98.7
Mg total		0.81	4.8
P available	mg·kg ⁻¹ DM	12.6	–
K available		22.5	–
Mg available		28.2	–

The content of heavy metals in the municipal sewage sludge did not exceed values allowing for its agricultural use. In the sewage sludge, no acceptable levels of microbiological pollution were exceeded (Regulation 2015).

Scheme and conditions of conducting the field experiment

The experimental design comprised two treatments. The treatment with mineral fertilization (1) was fertilized only with mineral fertilizers in the amount of 60:50:70 kg NPK·ha⁻¹. Nitrogen fertilizer was applied in the form of urea (46% N), phosphorus fertilizer – in the form of triple superphosphate (46% P₂O₅), and potassium was applied in the form of potassium chloride (50% K₂O).

The second treatment (2) was fertilized with municipal sewage sludge at a dose of 5.34 Mg·ha⁻¹ DM, which corresponded to 24 Mg·ha⁻¹ of fresh matter. The sludge was applied in the autumn and distributed with a manure spreader, and then pre-winter plowing was done. The sludge contained 118 kg N, 19.5 kg P, and 13.5 kg K. The amount of the sewage sludge dose applied under spring barley corresponded with the nitrogen requirement of the assumed yield of this plant. It is assumed that utilization of nitrogen from sewage sludge by cultivated plants amounts to approximately 50% in the first year (Aşyk and Katkat 2010, Gondek 2012). Hence, utilization of nitrogen from municipal sewage sludge by spring barley was assumed in the field experiment to be at a level of approximately 60 kg·ha⁻¹, which was comparable with the dose of this element in mineral form in the control treatment (1). Additionally, in the treatment with sewage sludge (2), fertilization was supplemented with phosphorus and potassium to the level applied in the control treatment (1).

In the third decade of March, «Rataj» cultivar spring barley was sown at a density of 400 germinating grains per 1 m², and harvest was carried out in the second decade of July.

Methodology of the research

From both treatments of the experiment, samples of spring barley grain and straw and soil samples (from a 0–25 cm layer) were collected from four representative areas of 15 m² each. Once the spring barley samples were collected, the plant material was dried in a forced air circulation dryer at 105°C, according to the widely adopted methodology of chemical-agricultural analysis. After drying the samples, the yield of the absolutely dry matter of spring barley

grain and straw was determined. The samples were then subjected to dry mineralization in a muffle furnace at 600°C (Ostrowska et al. 1991).

After drying and sifting through a 2 mm sieve, pH was determined in the soil by potentiometric method, in 1 mol·dm⁻³ KCl, organic carbon content was determined by Tiurin method, total nitrogen content – by Kjeldahl method, the content of available phosphorus and potassium – by Egner-Riehm method, and the content of available magnesium – by Schachtschabel method. The content of Fe, Mn, Co, Al in the soil was determined after digesting it in a mixture of concentrated acids: HNO₃ and HClO₄, (3:2, v/v). The content of these elements in the soil and in mineralized plant material (Jones and Case 1990, Ostrowska et al. 1991) was determined using atomic emission spectrometer Perkin Elmer Optima 7300 DV Spectrometer ICP-OES. The accuracy of the analytical method was verified against certified reference materials and standard solutions: CRM IAEA/V – 10 hay (International Atomic Energy Agency), CRM – CD281 – rye grass (Institute for Reference Materials and Measurements), CRM 023-050 – heavy metals – sandy clay 7 (RT Corporation).

The laboratory test results were elaborated statistically by the method of analysis of variance. Significance of differences between means were determined using Tuckey test at a significance level of $\alpha \leq 0.05$.

The uptake (U) the analyzed elements by spring barley was calculated as the product of dry matter yield (Y) and the element content (C) in grain and straw, according to the formula: $U = Y \cdot C$. This paper presents the utilization (recovery) of these elements by spring barley, which is defined as the percentage share of the amount of an element taken up by the plant in the total amount of this element introduced into soil together with municipal sewage sludge. This paper also shows mass ratios between the studied elements in spring barley biomass (Fe:Mn, Fe:Al, Fe:Co, Mn:Al, Mn:Co).

RESULTS AND DISCUSSION

Due to considerable richness in organic matter and mineral nutrients in municipal sewage sludge (from a non-industrialized commune) used in the experiment, agricultural use of this sludge appears to be environmentally and economically justified (Epstein 1975, Lundin et al. 2004, Peruzzi et al. 2011).

Basic soil properties

The dose of 5.34 Mg·ha⁻¹ DM of municipal sewage sludge applied under spring barley did not change soil basic properties (Table 2). There was no significant effect of application of used sewage sludge on lowering soil pH, whereas Domene et al. (2010), Murtaza et al. (2011) as well as Paz-Ferreiro et al. (2012) showed in their studies that the use of municipal sewage sludge in agriculture caused an increase in soil acidity. It is associated with the presence of acid substances generated as a result of microbiological decomposition and humification of organic matter (Gregorich et al. 2015).

TABLE 2. Chemical properties of soil from experimental plots after experiment

Treatment	pH _{KCl}	C	N	P	K	Mg
		total	total	available forms		
		g·kg ⁻¹ DM		mg·kg ⁻¹ DM		
1	7.0a*	21.0a	1.1a	12.7a	24.0a	29.8a
2	6.9a	21.2a	1.2a	12.9a	24.5a	30.5a

* values labeled with the same letters do not differ significantly among themselves according to Tukey's test, at a significance level of $\alpha \leq 0.05$.

A statistically insignificant increasing trend in the content of organic carbon, total nitrogen and of available forms phosphorus, potassium and magnesium was observed in the presented experiment. The slight increase in the content of macroelements improved soil fertility, and in consequence increased the yields of spring barley grown in the experiment. A similar yield-forming effect due to the use of sewage sludge and mineral fertilization was observed also by other authors (Wei and Liu 2005, Fischer et al. 2011, Gondek 2012, Lošák et al. 2016). As a rule, using municipal sewage sludge increases the content of organic carbon, total nitrogen and available forms of P, K, Mg, which found confirmation in the studies by Moreno et al. (2003) and Shaheen et al. (2014). Other authors confirm that municipal sewage sludge can be used to improve chemical and biological properties of soil (Gondek 2012, Kołodziej et al. 2016). Improvement of soil chemical properties is of considerable importance in making also microelements available for crops (Antolin et al. 2005, Gondek et al. 2012).

The average content of Fe, Al, Mn, Co in Polish soils is at an average level of 9600, 5800, 397, 3.91 mg·kg⁻¹, respectively, and depends on firmness of soil (Kabata-Pendias and Szteke 2012). The content of the studied elements in the soil on which the experiment was set up was above these averages, which might have had a considerable effect on the uptake of the

analyzed elements by spring barley. The soil on which the experiment was conducted had the most Fe (11225 mg), then Al (8562 mg), Mn (569.5 mg), and the least Co (5.78 mg·kg⁻¹ DM). The determined content of Fe, Al, Mn, Co exceeded average values for Polish soils by 17, 48, 43 and 48%, respectively.

Spring barley yield

The carried out field experiment showed that application of municipal sewage sludge for fertilizing purposes had a significant effect on spring barley yield. Grain and straw yield obtained from the treatment with mineral fertilization (1) amounted to 4.20 and 3.10 Mg, respectively, and from the treatment with sewage sludge (2) it was 4.80 and 3.50 Mg·ha⁻¹DM, respectively. Application of municipal sewage sludge increased the grain and straw yields by 14.2 and 12.9%, respectively, in relation to the treatment with an equivalent dose of mineral fertilizers. Antolin et al. (2005), Singh and Agrawal (2008), Gondek (2012) and Wieczorek (2013) also confirmed in their studies the yield-forming effect of application of sewage sludge in cultivation of cereals.

Content of Fe, Mn, Co, Al in spring barley

The content of elements in cereals is determined by soil conditions, including availability as well as nutrient requirements and the level of fertilization (Sager and Hoesch 2006, Suchowilska et al. 2012). The content of elements in the biomass of studied spring barley was varied and depended on the fertilization treatment (Table 3). Application of municipal sewage sludge to the soil had a significant effect on the increase in the content of elements in spring barley yield. A higher content of Fe, Co and Al was determined in straw, and Mn in grain of spring barley. Other authors also describe similar relationships in the chemical composition of cereals (Szabó and Fodor 2006, Zeidan et al. 2010).

Spring barley grain, depending on its chemical composition, is used for consumer or feed purposes. In Poland, approximately 75% harvested grain of this plant is used for feed (Statistical Yearbook of Agriculture 2015). It is assumed that optimum quality feed should contain 40–80 mg Fe, 40–70 mg Mn, 0.07–0.12 mg Co·kg⁻¹ DM (Bergmann 1966, Szoszkiewicz and Znamirovski 1989, Falkowski et al. 1996, Falkowski et al. 2000). When assessing the feed value of spring barley grain in terms of the content of the studied elements, it was established that iron content was within the optimal value range.

TABLE 3. Content and uptake of nutrients by spring barley

Treat- ment	Part of plants	Fe	Mn	Co	Al
content (g·kg ⁻¹ DM)					
1	Grain	41.9a*	13.6a	0.007a	17.3a
2		59.4b	16.2b	0.016b	21.8b
1	Straw	75.4a	8.0a	0.031a	25.4a
2		88.1a	10.7b	0.057b	30.9b
optimum content** (mg·kg ⁻¹ s.m.)					
		40–80	40–70	0.07–0.12	–
uptake (g·ha ⁻¹)					
1	Grain	176.2a	57.2a	0.030a	72.6a
2		286.1b	77.7b	0.075b	104.8b
1	Straw	234.2a	24.6a	0.096a	78.4a
2		308.2b	37.4b	0.197b	108.0b

* values labeled with the same letters do not differ significantly among themselves according to Tukey's test, at a significance level of $\alpha \leq 0.05$; **based on: Szoszkiewicz and Znamirovski 1989, Bergmann 1966, Falkowski et al. 1996, Falkowski et al. 2000.

Grain obtained in the treatment where mineral fertilization was applied (treatment 1) had a deficit content of Co. Application of municipal sewage sludge increased the content of this metal above the optimal value. Mn content in barley grain, regardless of treatment, was below the optimal value.

The physiological role of aluminum in plants has not been entirely explained (Szatanik-Kloc and Ambrozewicz-Nita 2015). It is believed that aluminum is toxic to plants and limits their growth and development. The toxicity of aluminum is revealed especially under very acid soil conditions (Barker and Pilbeam 2007, Kanu et al. 2013), and the applied sewage sludge had alkaline reaction (Table 1). It can be concluded from scientific literature that Al content in cereal grain amounts to 30–70 mg·kg⁻¹ DM (Kabata-Pendias 2011). Aluminum content determined in the studied spring barley grain obtained from the treatment where municipal sewage sludge was applied was approximately 22 mg·kg⁻¹ DM (Table 3). This value is below the average content defined for cereals (Kabata-Pendias 2011).

When analyzing the content of the studied elements in spring barley straw, it was established that Fe content was within the optimal value range. It was established that the content of Mn and Co in barley straw, regardless of treatment, was below the optimal value.

The uptake of elements by spring barley

Microelement uptake by cereals is generally low and depends on soil conditions and on the level of fertilization (Pisulewska et al. 2009, Witkiewicz 2016).

The amount of uptaken micronutrients is also a result of nutrient requirements of this group of plants (Mackowiak et al. 2011, Witkowicz et al. 2015). Our research showed that element uptake by spring barley was varied and depended on the fertilization treatment (Table 3). A significantly positive effect of municipal sewage sludge on the uptake of these elements by spring barley was observed. The data in Table 3 indicate that more Fe, Co and Al was taken up with spring barley straw, and more Mn with grain. Spring barley (grain + straw) fertilized with sewage sludge took up the highest amount of Fe (594.4 g), followed by Al (212.8 g), Mn (115.1 g), whereas the lowest amount of Co was taken up (0.3 g·ha⁻¹). The increase in uptake of these elements was determined mainly by organic fertilization. Chen et al. (2007) as well as Gondek et al. (2012) also observed a significant effect of fertilization with municipal sewage sludge on the increase in the uptake of microelements by cereals.

The use of elements by spring barley

With the dose of 5.34 Mg ha⁻¹ dry matter of municipal sewage sludge, the soil was amended more than 9.88 kg Fe, 2.44 kg Mn, 0.04 kg Co and 28.52 kg Al·ha⁻¹. Utilization of these elements from municipal sewage sludge by spring barley was 6.02, 4.72, 0.68 and 0.75%, respectively. Iron was used by spring barley the most, and cobalt – the least. This research shows that the applied municipal sewage sludge in a dose of 5.34 Mg dry matter covered the demand for Fe, Mn, Co and Al by spring barley with surplus, and the remainder enriched the soil with these elements.

Mass ratios between elements in spring barley

Quantitative ratios between elements in plants constitute an important qualitative aspect for the chemical composition and the nutritional or feed value of crops (Mackowiak et al. 2011, Antonkiewicz 2014, Witkowicz et al. 2015). Table 4 presents mass ratios between the studied elements present in the biomass of spring barley.

TABLE 4. Ratios between elements in spring barley

Treat- ment	Part of plants	Fe:Mn	Fe:Al	Fe:Co	Mn:Al	Mn:Co
1	Grain	3.1a*	2.4a	6045b	0.79a	1969b
2		3.7a	2.7a	3997a	0.74a	1114a
1	Straw	9.6a	2.9a	2463b	0.31a	257b
2		8.3a	2.8a	1578a	0.35a	191a

* values labeled with the same letters do not differ significantly among themselves according to Tukey's test, at a significance level of $\alpha \leq 0.05$.

It was established that the analyzed ratios (Fe:Mn, Fe:Al, Mn:Co) were much wider in straw than in grain (Table 4). The analysis of mass ratios indicates that spring barley grain, obtained regardless of treatment, had a very low variability of ratios between these chemical elements. The conducted research shows that applied municipal sewage sludge significantly decreased the ratio between Fe:Co and Mn:Co, both in grain and straw of spring barley.

The obtained biomass of spring barley was evaluated based on the criterion of feed nutrient value, according to which the optimal Fe:Mn ratio is 1.5–2.5:1 (Liwski 1961, Mackowiak et al. 2011). When evaluating spring barley grain and straw, it was established that the analyzed value of the Fe:Mn ratio was below the optimal value. It is indicative of a high iron content and a deficit content of manganese.

CONCLUSIONS

1. When evaluating the grain from the treatment fertilized with municipal sewage sludge in terms of feed value, the optimum Fe content was determined, whereas the content of Mn and Co was above the optimal value.
2. Barley cultivated after application of municipal sewage sludge generally accumulated higher amounts of the studied elements than when only mineral fertilizers were used.
3. Barley grain and straw accumulated elements in descending order: Fe, Al, Mn and Co.
4. Utilization of Fe, Mn, Co and Al from the studied sewage sludge by spring barley was, respectively, 6.0, 4.7, 0.7 and 0.7% of the amount applied to the soil with this material.
5. In terms of quality, Fe:Mn ratio in grain and straw was greater than optimum, which is indicative of a high iron content and a deficit content of manganese.
6. The applied municipal sewage sludge significantly decreased the Fe:Co and Mn:Co ratios in grain and straw of spring barley.

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Received: January 9, 2017

Accepted: May 12, 2017

Associated editor: B. Rutkowska

Wpływ komunalnego osadu ściekowego na zawartość, wykorzystanie i stosunki masowe wybranych składników w biomase jęczmienia jarego

Streszczenie: Komunalne osady ściekowe zawierają znaczne ilości makroelementów oraz mikroelementów niezbędnych w żywieniu roślin. Przy zmniejszającym się stosowaniu nawozów naturalnych i organicznych istnieje potrzeba poszukiwania alternatywnych źródeł substancji organicznej, będącej substratem do reprodukcji próchnicy glebowej. W doświadczeniu łanowym przeprowadzonym na glebie ciężkiej o odczynie obojętnym, porównano działanie jednorazowego zastosowania komunalnych osadów ściekowych w dawce 5,34 Mg·ha⁻¹ s.m. z równoważną dawką nawozów mineralnych. Rośliną testową był jęczmień jary. Po zastosowaniu komunalnych osadów ściekowych stwierdzono niewielkie, korzystne zmiany właściwości chemicznych gleby. Komunalny osad ściekowy wpłynął na zwiększenie plonu ziarna i słomy jęczmienia jarego odpowiednio o: 14 i 13% w stosunku do obiektu z nawożeniem mineralnym. Jęczmień jary nawożony osadami ściekowymi zawierał więcej składników w porównaniu do uprawianego na samych nawozach mineralnych. Wykazano, że zastosowanie komunalnych osadów ściekowych do gleby wpłynęło istotnie na zwiększenie pobrania składników przez jęczmień jary. W największej ilości pobrane zostało Fe, następnie w kolejności Al, Mn, a najmniej Co. Wykorzystanie Fe, Mn, Co i Al z osadów ściekowych przez jęczmień jary kształtowało się na poziomie odpowiednio: 6,0; 4,7; 0,7 i 0,7% ilości zastosowanej do gleby z tym odpadem. W biomase jęczmienia jarego analizowane stosunki masowe Fe:Mn, Fe:Al, Mn:Co były znacznie szersze w słomie niż w ziarnie. Z punktu widzenia wartości paszowej ziarna wartość proporcji Fe:Mn w ziarnie i słomie była większa od optymalnej.

Słowa kluczowe: jęczmień jary, plony, osad ściekowy, pobranie, Fe, Mn, Co, Al