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Energy crops cultivated on the slag from incineration of the sewage sludge energy value assessment

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Abstract. In 2011–2013, research on the fertilizer value of slag from the incineration of municipal sewage sludge as an alternative source of phosphorus was carried out. The research scheme included 5 variants (in 4 repetitions) fertilization cultivated for grain with mineral fertilizers and ash. (P1, P2 and P3 – consecutive doses of phosphorus from ash) from municipal sewage sludge combustion: NK, NPK, NK+P1, NK+P2 and NK+P3. The obtained results indicate that the average of the three years of research, the value for the straw spring rape heat of combustion was 15.99 MJ/kg d.m., corn straw 16.20 MJ/kg d.m., triticale straw 17.06 MJ/kg d.m. and Miscanthus 17.34 MJ/kg d.m. The highest value of combustion heat for spring rape straw and miscanthus performed for objects fertilized with NK + P3 – 16.08 MJ/kg d.m. (Spring rape) and 17.57 MJ/kg d.m. (Miscanthus); For corn straw objects fertilized with nitrogen and potassium – 16.35 MJ/kg d.m. and triticale straw objects fertilized with NPK and NK + P2 – 17.10 MJ/kg d.m. Straw calorific value of tested plants was lower than the combustion heat by an average of 6.97% (triticale) to 7.38% (spring rape).

1 Introduction

In accordance with the National Waste Management Plan 2014 [1], by 2022, as part of the municipal sewage sludge management, the mass of sludge processed thermally will be increased and the use of nutrients from the sludge will be maximized. Strategy for development of municipal sewage sludge by means of thermal processing according to [2] is fully valid; in some countries of the European Union (Switzerland) it covers almost 100% of weight, while in others (Germany) it exceeds 50%. Currently, 11 incineration

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plants of municipal sewage sludge operate in Poland and the need to increase thermal processing in the sludge management strategy will force the construction of subsequent incineration plants, especially in large urban areas [3].

Combustion of municipal sewage sludge generates a new kind of waste e.g. ashes and slag and produces gases polluted by dust, oxides of carbon, nitrogen, sulphur, heavy metals and hydrocarbons [4].

Wzorek [5] stated that in accordance with “the principles of sustainable development”, the search for alternative sources of phosphorus, and in particular, the possibility of its recovery and recycling of waste should be classified as priority issues of the phosphoric industry. She points out the most important actions, such as recovery of phosphorus from urban and industrial waste water, sewage sludge, poultry manure and from meat industry waste. In order to avoid phosphorus deficit, some researchers propose to release soil phosphorus reserves unavailable to plants or from waste with phosphorus content e.g. by means of using appropriate microorganisms causing solubilisation of phosphorus compounds [6–8].

By analysing chemical composition, attention was drawn to the high content of phosphorus in ashes from the incineration of municipal sewage sludge, which can exceed even 9.61 $gP \cdot kg^{-1}$ d.m. [9].

The purpose of the research was to determine the influence of slag from the combustion of municipal sewage sludge on the contents of macronutrients in the straw, the calorific value and the heat of the combustion of plants.

2 Research material and methods

In the years 2011–2013, in the Agricultural Experimental Station in Lipnik near Stargard, tests have been carried out to fertilize plants using slag (fraction of less than 2 mm) from the combustion of municipal sewage sludge.

A field experiment was conducted on brown and red, incomplete soil produced from light, dusty clay sand, with average deep sediments of light clay. The scheme of the research covered five variants of fertilization with mineral fertilizers and slag from the combustion of municipal sewage sludge: NK, NPK, NK + P1 (P1 – 1 dose of ash – 50 kg $P_2O_5 \cdot ha^{-1}$), NK+P2 (P2 – 2 dose of ash – 100 kg $P_2O_5 \cdot ha^{-1}$), NK+P3 (P3 – 3 dose of ash – 150 kg $P_2O_5 \cdot ha^{-1}$). The slag from the combustion of municipal sewage sludge came from the Sewage Treatment Plant “Pomorzany” in Szczecin. The waste code – 19 01 12. Direct soil application of slag as phosphorous fertilizer was conditioned by the fulfilment of the requirements defined in the Regulation of the Minister of Agriculture and Rural Development [10]. The slag contained from 16.30 to 22.05% of total P_2O_5 soluble in strong mineral acids and from 9.98 to 12.08% of P_2O_5 soluble in 2% citric acid (Table 1). This waste was applied under: grain maize (variety DKC-FAO 240), spring rape (variety Larissa – 2011, variety Markus – 2012, variety Clipper – 2013), spring triticale (variety Milkaro), and giant miscanthus. Plants were also fertilized with nitrogen and potassium, in accordance with the recommended doses.

The research scheme included 5 variants (in 4 repetitions) fertilization cultivated for grain with mineral fertilizers and ash. (P1, P2 and P3 – consecutive doses of phosphorus from ash) from municipal sewage sludge combustion: NK, NPK, NK+P1, NK+P2 and NK+P3. Nitrogen pre-sowingly was used in the form of ammonium sulphate (20% N and 24%S), and ammonium nitrate for top dressing (34% N). On the other hand, phosphorus in the dose of 21.80 kg $P \cdot ha^{-1}$ (enriched superphosphate 17.44% P) and potassium in the dose of 91.30 kg $K \cdot ha^{-1}$ (potassium salt 49.80% K) in mineral fertilizers were used only pre-sowingly annually. What is more, ash was also used pre-sowingly in the following doses:

P1 – 21.80, P2 – 43.60 and P3 – 65.40 kg·ha^{-1} of phosphorus dissolvable in strong mineral acids.

The slag from the combustion of municipal sewage sludge, which provided a substitute for phosphorous fertilizer, came from Sewage Treatment Plant "Pomorzany" in Szczecin. The chemical composition is given in Table 1.

Table 1. Chemical composition of ash from municipal sewage sludge combustion [11].

Year of study	Content of forms soluble P [%]			Total content of [%]		
	in strong mineral acids	in 2 % citric acid	in water	K	Ca	Mg
2011–2012	9.613	5.266	3.331	4.260	6.220	3.870
2013	7.106	4.351	2.241	4.960	6.970	4.670
Total content of [mg·kg^{-1} d.m.]						
Year of study	Cd	Cu	Mn	Ni	Pb	Zn
2011–2012	4.160	476.2	411.4	74.70	93.00	745.1
2013	2.390	310.3	476.9	18.00	84.30	820.2

Total phosphorus content (P) soluble in strong mineral acids in the ash used in 2011–2012 was 9.61% and in 2015 − 7.11%. Moreover, ashes contained 4.26 and 4.96% of potassium, 6.22 and 6.97% of calcium and 3.87% of magnesium in 2011–2012 and 4.67% in 2013.

Heavy metals content did not exceed quantities established under the Regulation of the Minister of Environment (2010) on Municipal Sewage Sludge.

Test plants included: spring rape, maize, spring triticale and miscanthus. The mass of individual parts of the yield was defined, samples were taken and dried at 60°C. In such dry straw, after creating a medium-sized object samples, it was determined: the dry matter using the dry oven test (105°C); total N and S − using the CNS analyser manufactured by the Costeh company; P − using the Barton method; K, Ca and Mg using the ASA method, after mineralization of samples in the mixture (3:1) of nitric acid (V) and chloric acid (VII). Heat of combustion with the determined calorific value (according to PN-EN-ISO 9931:2005) was measured in the IKA 2004 calorimeter with uncertainty of measurement of the calorific value of 44 kJ/kg d.m. Multiple comparison of average values was conducted using the Tukey procedure, at $p = 0.05$. The standard deviation (SD) for the content of the macronutrients in a test plant was calculated according to STATISTICA 10 [12].

3 Results and discussion

Total macronutrients content in the straw (spring rape, maize, triticale and miscanthus) was presented as the average from the years of research (Table 2 and 3). The average nitrogen content (15.950 ± 1.161 gN·kg^{-1} d.m.) in the spring rape straw from individual objects was not diverse and ranged from 14.110 to 17.330 gN·kg^{-1} d.m. The average N content in the maize straw was 8.370 ± 0.559 gN·kg^{-1}d.m., and ranged from 7.641 to 9.002 gN·kg^{-1} d.m. In the spring triticale straw: 7.136±0.160 gN·kg^{-1} d.m., and in miscanthus: 8.450 ± 0.273 gN·kg^{-1} d.m.

Small diversity of the nitrogen content in the plant straw is probably associated with the same dose of this component in all fertilizing variants. The research conducted by [13], shows that even a big difference in the dose of nitrogen or the type of the phosphorous fertilizer does not cause significant changes in the content of this nutrient in maize.

Greater differences were expected in the case of the phosphorus content in plant straw, as doses in individual objects were varied. In the plant straw from objects NK, NPK, NK+P1 and NK+P2, similar phosphorus content was found, which varied: in spring rape 4.240–4.580 gP·kg^{-1} d.m., in maize 4.155–4.501 gP·kg^{-1} d.m., in spring triticale 1.292–1.336 gP·kg^{-1} d.m. and in miscanthus 3.740–4.420 gP·kg^{-1} d.m. The same dose of potassium (91.30 kgK·ha^{-1}) was used in all objects in the form of potassium salt. However, in versions with the ashes from the combustion of sewage sludge, additional potassium was used (from 6.74 to 20.22 kgK·ha^{-1} within a period of three years), which had no effect on its contents in the maize straw (12.211 ± 0.220 gK·kg^{-1} d.m.) (Tab. 2). In conclusion, it was found that the test plants were well nourished with potassium [14].

The biggest average calcium content (Tab. 3) was found in the spring rape straw and amounted to 18.370 ± 1.192 gCa·kg^{-1} d.m., and the smallest in the spring triticale straw 3.073 ± 10.416 gCa·kg^{-1} d.m.

The content of macronutrients in plants depends on several factors, including climate, soil and variety. By analysing the chemical composition of four varieties of maize, [15] obtained smaller phosphorus content (2.010 g P·kg^{-1} d.m.), potassium (1.980 gK·kg^{-1} d.m.), calcium (0.300 gCa·kg^{-1} d.m.), and magnesium (1.170 gMg·kg^{-1} d.m.), more in the maize and miscanthus straw than in the presented studies.

The average sulphur content in the straw of the test plants (Tab. 3) was not significantly varied and amounted to: in spring rape 3.200–5.510 gS·kg^{-1} d.m., in maize 0.820–1.050 gS·kg^{-1} d.m., in spring triticale 1.003–1.376 gS·kg^{-1} d.m. and in miscanthus 0.709–0.958 gS·kg^{-1} d.m.

Table 2. The average of the three-year content of macronutrients in the straw of test plants.

Objects	**N**				**P**				**K**			
	Spring rape	**Maize**	**Spring triticale**	**Miscanthus**	**Spring rape**	**Maize**	**Spring triticale**	**Miscanthus**	**Spring rape**	**Maize**	**Spring triticale**	**Miscanthus**
NK	14.110	8.401	7.172	8.100	4.090	3.821	1.349	3.670	12.000	12.155	9.272	10.570
NPK	15.150	7.855	7.421	8.850	4.240	4.286	1.363	3.900	14.780	11.866	9.360	10.060
NK + P1	16.600	8.946	6.946	8.240	4.580	4.155	1.336	4.420	14.210	12.441	8.776	9.680
NK + P2	16.570	7.629	7.057	8.660	4.120	4.287	1.363	3.740	13.450	12.135	8.801	8.870
NK + P3	17.330	8.963	7.083	8.400	4.330	4.501	1.292	3.970	13.450	12.457	9.885	9.510
Average	15.950	8.359	7.136	8.450	4.270	4.210	1.340	3.940	13.580	12.211	9.219	9.740
Standard deviation	1.161	0.547	0.160	0.273	0.176	0.224	0.026	0.263	0.935	0.220	0.409	0.567

Table 3. The average of the three-year content of macronutrients in the straw of test plants.

Objects	**Ca**				**Mg**				**S**			
	Spring rape	**Maize**	**Spring triticale**	**Miscanthus**	**Spring rape**	**Maize**	**Spring triticale**	**Miscanthus**	**Spring rape**	**Maize**	**Spring triticale**	**Miscanthus**
NK	18.280	9.040	3.187	5.536	0.640	10.870	0.207	1.265	3.200	0.880	1.376	0.832
NPK	16.750	11.220	3.373	5.719	0.680	10.040	0.207	1.370	4.760	0.820	1.150	0.928
NK + P1	19.350	12.210	3.500	6.535	0.660	11.080	0.207	1.429	4.690	0.870	1.176	0.958
NK + P2	17.480	11.100	2.988	5.321	0.770	10.970	0.182	1.382	5.480	0.850	1.094	0.885
NK + P3	20.020	9.940	2.317	5.552	0.810	10.160	0.168	1.345	5.510	1.050	1.003	0.709
Average	18.370	10.700	3.073	5.733	0.710	10.620	0.194	1.358	4.730	0.890	1.160	0.862
Standard deviation	1.192	1.099	0.416	0.421	0.066	0.435	0.016	0.054	0.838	0.081	0.123	0.088

The obtained results indicate that the average value from three years of research for heat of combustion from spring rape straw was 15.99 MJ/kg d.m., from maize straw 16.20 MJ/kg d.m., from spring triticale straw 17.06 MJ/kg d.m., and from miscanthus 17.34 MJ/kg d.m. The biggest value of the heat of combustion from spring rape and miscanthus straw occurred for objects fertilized with NK+P3 – 16.08 MJ/kg d.m. (spring rape) and 17.57 MJ/kg d.m. (miscanthus). For maize straw objects fertilized with nitrogen and potassium – 16.35 MJ/kg d.m., and spring triticale straw for objects fertilized with NPK and NK+P2 – 17.10 MJ/kg d.m. The calorific value of straw from test plants was smaller than the heat of combustion by 6.97% (spring triticale) –7.38% (spring rape) (Table 4).

Table 4. The average of three years of burning heat and calorific value of straw test plants.

Objects	**Heat of combustion**				**Calorific value**			
	Spring rape	**Maize**	**Spring triticale**	**Miscanthus**	**Spring rape**	**Maize**	**Spring triticale**	**Miscanthus**
NK	15.93	16.35	17.06	17.21	14.82	15.17	15.86	15.98
NPK	15.96	16.27	17.10	17.31	14.60	15.09	15.91	16.08
NK + P1	15.98	16.25	17.09	17.19	14.59	15.06	15.89	15.97
NK + P2	16.02	16.24	17.11	17.41	14.62	15.06	15.91	16.19
NK + P3	16.08	15.89	16.97	17.57	14.90	14.71	15.78	16.35
Average	15.99	16.20	17.07	17.34	14.70	15.02	15.87	16.11
Standard deviation	0.052	0.160	0.051	0.140	0.129	0.159	0.049	0.142

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4 Conclusions

1. The average yield of grain and straw in particular years and for from three years of research was not significantly different between the objects fertilized with mineral fertilizers (NK and NPK) and with mineral fertilizers including the ash from the combustion of municipal sewage sludge.
2. The average content of N, K, Mg, and S in the straw of the test plants was not diverse. Only the highest dose of the ash from the combustion of sludge increased the total phosphorus content in the straw by 6.18%, compared with NPK.
3. The average value from three years of research for heat of combustion from spring rape straw was 15.99 MJ/kg d.m., from maize straw 16.20 MJ/kg d.m., from spring triticale straw 17.06 MJ/kg d.m., and from miscanthus 17.34 MJ/kg d.m. The biggest value of the heat of combustion from spring rape and miscanthus straw occurred in objects fertilized with NK+P3 – 16.08 MJ/kg d.m. (spring rape) and 17.57 MJ/kg d.m. (miscanthus).
4. The use of slag resulting from thermal processing of sewage sludge as phosphorous fertilizer does not affect the contents of macronutrients in the test plants. In most cases, fertilization with raw slag improved energy performance of the plant straw.

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