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YIELDS OF GRAIN AND STRAW, THEIR CONTENT AND IONIC PROPORTIONS OF MACROELEMENTS IN MAIZE FERTILIZED WITH ASH FROM MUNICIPAL SEWAGE SLUDGE COMBUSTION*

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Abstract

In 2011-2013, research was conducted on the fertilizer value of ash from municipal waste combustion used as an alternative source of phosphorus. A field experiment was set up on light soil. The design included 5 fertilization variants of maize, which was cultivated for grain and fertilized with mineral fertilizers and ash (P1, P2, P3): NK, NPK, NK+P1 (P1−21.80 kg P ha^{-1}), NK+P2 (P2−43.60 kg P ha^{-1}), NK+P3 (P3−65.40 kg P ha^{-1}). Nitrogen (80 kg N ha^{-1}) was applied in the form of ammonium sulphate and ammonium nitrate, phosphorus (21.80 kg P ha^{-1}) as enriched superphosphate and potassium (91.30 kg K ha^{-1}) as potassium salt. Ash, which was a substitute for phosphorus fertilizer, was obtained from the Pomorzany Sewage Treatment Plant in Szczecin in 2011-2013. It included 9.61%, and in 2013 – 7.11% of total P dissolvable in strong mineral acids. Maize harvest was done in the phase of full ripeness, afterwards the mass of grain and straw was determined as well as the total content of N, P, K, Ca, Mg and S in both yield components. The years with favourable weather conditions fostered high maize grain yield (average 10.75 Mg d.m. ha^{-1}) and maize straw (average 10.06 Mg d.m. ha^{-1}). Ash from sewage sludge combustion did not cause any significant differences in the crop volume in the particular years of research, in comparison with crop from NK and NPK treatments. The weighted average total content of macroelements in maize grain and straw from particular fertilization treatments did not vary widely, and only the highest dose of ash (P3) increased the average content of phosphorus in maize grain and straw as well as calcium in maize grain when compared to NPK. Regardless of the fertilization variant, and in relation to the feed value, an optimal N:S and ionic ratio was found in maize grain, while the ionic proportions between K:Mg and K:(Ca+Mg) were close to optimal ones. Independently of a fertilization variant, the balance of elements was negative for nitrogen and phosphorus and positive for sulphur.

Key words: ash from sewage sludge combustion, maize, macroelements, proportions of macroelements.

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INTRODUCTION

One of the important concerns about the environment is how to improve the municipal sewage sludge management. According to the *National Waste Management Plan* (2014), the mass of waste converted thermally will be increased and the use of nutrients from sludge will be maximized in municipal sewage sludge management until 2022. According to PAJĄK (2010), the strategy promoting thermal municipal sewage sludge management is justifiable, and in some countries nearly 100% (Switzerland) while in others over 50% (Germany) of such waste treatment by-product is recycled. Currently, there are over 10 municipal sewage sludge combustion plants in Poland, and the need to increase thermal conversion in the sludge management strategy will necessitate the construction of new combustion plants, especially in large urban areas (BIEŃ 2012).

Municipal sewage sludge combustion generates a new type of waste, such as ash and slag. Moreover, gases which become polluted by dust, carbon monoxide, nitrogen monoxide, sulphur monoxide, heavy metals and hydrocarbons are generated (FUKAS-PŁONKA 2013). Disposal of contamined gases is quite simple and takes place at a treatment plant, while the management of big masses of ash and slag is more difficult.

WZOREK (2008) stated that according to the principles of sustainable development the search for alternative sources of phosphorus, and especially the possibility of its recovery and recycling from waste, should be classified as a priority issue for the phosphoric industry. The most important action the author considers is the recovery of phosphorus from municipal and industrial wastewater, sewage sludge, poultry manure and meat industry waste. In order to avoid deficit of phosphorus, some researchers propose to ativate the soil phosphorus reserves which are inaccessible to plants or the ones from waste containing phosphorus i.e. by deploying microorganisms that cause solubilization of phosphorus (RODRIGUEZ et al. 1999, SUNDARA et al. 2002, SAEID et al. 2012), as well as through genetic improvement of plants regarding their more efficient use of mineral components, including phosphorus (CIERESZKO 2005).

When analyzing the chemical composition, attention was drawn to the high content of phosphorus in ashes from municipal sewage sludge combustion, which might even exceed 87 g P kg^{-1} d.m. (IŻEWSKA, WOŁOSZYK 2013). Phosphorus-rich waste (ashes, ash-slag, slag) from municipal sewage sludge combustion, as well as its increasing amounts stimulated to the current research on its use for plant fertilization.

The aim of this study was to determine the influence of ash from municipal sewage sludge combustion on yield as well as on the content and ionic ratios of macroelements in maize grain and straw.

MATERIAL AND METHODS

In 2011-2013, a research experiment was conducted in the Agricultural Experimental Station in Lipnik near Stargard Szczeciński, on the use of municipal sewage sludge combustion ash for plants fertilization. A field experiment was located on brown-rusty soil, incomplete soil, produced from light, dusty loamy sand, covered with light clay to an average depth (valuation class IVb, good rye complex – 5). Prior to the experiment, soil pH was slightly acidic (pH in 1 mol KCl dm^{-3} – 5.80), the total content of carbon was 8.59 g, nitrogen 0.84 g kg^{-1}, the content of assimilable forms of phosphorus was high, whereas the levels of potassium and magnesium were low.

The research scheme included 5 variants (in 4 replications) of the fertilization of maize cultivated for grain, supplied 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. Pre-sowing nitrogen was applied in the form of ammonium sulphate (20% N and 24%S), while ammonium nitrate was used for top dressing (34% N). On the other hand, phosphorus in the dose of 21.80 kg P ha^{-1} (enriched superphosphate 17.44% P) and potassium in the dose of 91.30 kg K ha^{-1} (potassium salt 49.80% K) in mineral fertilizers were used each year only before sowing. Moreover, ash was also used pre-sowing in the following doses: P1 – 21.80, P2 – 43.60 and P3 – 65.40 kg ha^{-1} of phosphorus dissolvable in strong mineral acids.

Ash from municipal sewage sludge combustion, which was a substitute for phosphorus fertilizer, was obtained from the Pomorzany Sewage Treatment Plant in Szczecin. The chemical composition of ash is presented in Table 1.

Table 1

Chemical composition of ash from municipal sewage sludge combustion

Year of study	Content of forms soluble P (%)			Total content (%)		
	in strong mineral acids	in 2% citric acid	in water	K	Ca	Mg
2011-2012	9.61	5.27	3.33	4.26	6.22	3.87
2013	7.11	4.35	2.24	4.96	6.97	4.67
Total content (mg kg^{-1} d.m.)						
Year of study	Cd	Cu	Mn	Ni	Pb	Zn
2011-2012	4.160	476.20	411.40	74.70	93.00	745.10
2013	2.390	310.30	476.90	18.00	84.30	820.20

The total content of phosphorus (P) dissolvable in mineral acids in ash applied in 2011-2012 was 9.61%, and in 2013 – 7.11%. Moreover, ashes contained 4.26 and 4.96% of potassium and 6.22 and 6.97% of calcium and 3.87% in 2011-2012 and 4.67% of magnesium in 2013. The content of heavy metals did not exceed thresholds set by the *Regulation of the Ministry of the Environment* (2010) on municipal sewage sludge.

Maize of DKC 3016 – FAO 240 variety was tested annually. It was cultivated after winter wheat in the first year, after spring oilseed rape in the second year, and after spring triticale in the third year. Maize (in the density of 75 thousand grains per ha) was sown on 28.04.2011, 05.05.2012 and 26.04.2013.

Maize was protected twice against pests and once against weeds during the vegetation period. Harvesting of whole maize plants was done manually (18.10.2011, 04.10.2012 and 19.09.2013), after which cobs were separated from the other parts of plants. After manual threshing of the cobs, the mass of grains and straw was determined (stems with leaves, rachis and maizecob integuments).

The weight of particular parts of the crop was determined. Samples were taken from the crop and dried at 60°C. In the dried grains and straw, after creating medium-size object samples, the following were determined: the content of dry mass with the oven-drying method (at 105°C), the total content of N and S – on an CNS analyzer produced by Costeh, P – with the Barton method, K, Ca and Mg – with the ASA method, after prior mineralization of samples in a mixture (3:1) of nitric(V) and chloric(VII) acids. The variance analyses of maize yield results in randomized blocks were performed with FR-ANALWAR 4.3. software. The means were compared with the Tukey procedure, at $p = 0.05$. Standard deviation for the content of macroelements in the tested plant was calculated with Statistica 10 Program.

The atmospheric conditions during the maize growing period in 2011-2013 were expressed as average monthly air temperatures and monthly sums of precipitation. They were subsequently compared to average amounts from a multiannual period (Table 2).

Table 2

Average monthly air temperatures (°C) and monthly sums of precipitation (mm) during the growth of maize plants in 2011-2013. Data from the Institutional Observation Point ZODR in Barzkowice, Wets Pomerania

Months	Temperatures				Precipitation			
	2011	2012	2013	average from multi-annual 1994-2010	2011	2012	2013	average from multi-annual 1994-2010
May	13.5	15.1	13.2	12.5	38.7	22.6	71.4	55.2
June	16.3	15.4	19.3	15.5	49.4	48.3	96.7	60.5
July	15.9	18.7	21.0	18.1	196.0	119.5	56.6	67.7
August	16.2	17.2	20.8	17.3	82.7	76.7	72.6	68.4
October	16.2	14.6	14.5	12.8	51.8	32.1	65.5	52.1
Average /total	15.6	16.2	17.8	15.2	418.6	309.2	362.8	254.2

RESULTS AND DISCUSSION

Throughout the research (2011-2013), high yields of maize grain were achieved, i.e. 10.75 Mg d.m. ha^{-1} on average (Table 3), which in 2013 exceeded the national average (6.58 Mg d.m. ha^{-1}) by over 63% (*Statistical year book* ... 2013). The high yielding of maize in the analyzed years, apart from

Table 3

Maize grain and straw yield (Mg d.m. ha^{-1})

Treatments	Grain				Straw			
	2011	2012	2013	average	2011	2012	2013	average
NK	10.13	11.99	9.88	10.67	10.06	11.21	8.42	9.90
NPK	10.33	11.08	9.98	10.46	9.21	11.73	8.42	9.79
NK+P1	11.01	12.23	10.10	11.11	9.65	12.14	8.99	10.26
NK+P2	10.29	11.21	10.18	10.56	9.45	11.77	9.01	10.08
NK+P3	10.68	11.93	10.16	10.92	9.90	12.26	8.69	10.28
Average	10.49	11.69	10.06	10.75	9.65	11.82	8.71	10.06

the agrotechnical factors, was owed to the favourable atmospheric conditions (Table 2). In each year, during the maize growing season (May-September), both the average air temperatures and precipitation sums exceeded the respective multiannual averages. The research results by Kruczek and Szulc (2005) show the significant impact of atmospheric conditions on maize yield, which reached 9.276 up to 10.65 Mg ha^{-1} of grain on good rye complex soil in years with favourable weather conditions, while declining to 5.938 Mg ha^{-1} in years poor in precipitation in July (e.g. 2002). The research by Lepiarczyk et al. (2013) indicates that the agricultural soil usability complex is another important yielding factor. In 2008-2010, depending on mineral fertilization, the average maize grain yield was 12.03 Mg ha^{-1} on good rye complex soil, which is about 1 Mg ha^{-1} more than in the present research.

The maize grain yield achieved in the particular years, as well as the average crop of grain from the three years of research did not vary widely. The highest average crop of maize grain (11.11 Mg ha^{-1}) was collected from the NK+P1 treatment, and in the other treatments the crop of grain was lower from 0,190 to 0.650 Mg ha^{-1}. Fertilizing with mineral fertilizers and ash from municipal sewage sludge combustion also failed to diversify the crop of maize straw significantly (Table 3), and the highest average crop was collected from the NK-P3 treatment (10.28 Mg d.m. ha^{-1}), whereas the lowest from the NPK treatment (9.79 Mg d.m. ha^{-1}).

The research by Kruczek and Szulc (2005) showed no diversity of maize grain yield volume depending on the dose of phosphorus (2005). Those authors received very close average grain yields ranging from 8.603 to 8.932 Mg ha^{-1} using 4 doses of phosphorus (from 14.40 to 56.70 kg P ha^{-1}).

On the other hand, Potarzycki (2008) indicated that three types of phosphoric mineral fertilizers: simple superphosphate, triple superphosphate, and Lubofos PK, which includes partly acidulated phosphate, had the same impact on the volume of maize grain. On the basis of five-year experiments, the author concluded that partly acidulated phosphate might be an alternative source of phosphorus for maize cultivated for grain.

The total content of macroelements in maize grain and straw is presented as the weighted average derived from the three years of research (Table 4). The average content of nitrogen (13.69 ± 0.301 g N kg^{-1} d.m.) in maize grain from the particular treatments was slightly diversified and ranged from

Table 4

Weighted average (from three years) content of macroelements in maize grain and straw (g kg^{-1} d.m.)

Treatments	Grain			Straw		
	N	P	K	N	P	K
NK	13.72	5.932	4.704	8.455	3.799	12.40
NPK	13.98	5.717	4.084	7.847	4.271	11.89
NK+P1	13.22	5.938	4.376	8.960	4.181	12.47
NK+P2	14.03	5.952	3.963	7.641	4.243	12.04
NK+P3	13,51	7.605	5.055	9.002	4.535	12.51
Average	13.69	6.299	4.436	8.381	4.206	12.26
Standard Deviation	0.301	0.697	0.402	0.559	0.237	0.260
Treatments	Ca	Mg	S	Ca	Mg	S
NK	0.687	0.985	0.964	8.920	3.625	0.887
NPK	0.548	0.944	1.027	10.997	3.271	0.817
NK+P1	0.568	1.021	1.114	11.938	3.689	0.873
NK+P2	0.607	0.990	1.021	10.740	3.645	0.857
NK+P3	0.732	1.030	0.951	9.801	3.314	1.062
Average	0.628	0.994	1.015	10.479	3.509	0.899
Standard Deviation	0.070	0.030	0.057	1.036	0.180	0.085

13.22 to 14.03 g N kg^{-1} d.m. In maize straw, the average content of N was 8.381 ± 0.559 g N kg^{-1} d.m., and ranged from 7.641 to 9.002 g N kg^{-1} d.m. This small difference of the nitrogen content in maize biomass is most probablythe consequence of the equal doses of nitrogen used in all the fertilization variants and the slight diversification of maize yield volumes. Potarzycki (2009) implicated that neither a large difference in the dose of nitrogen (80 and 140 kg ha^{-1}) nor the type of phosphoric fertilizer caused any significant changes in the content of this component in maize grain.

More significant changes were expected in the case of the phosphorus content in maize grain and straw, because its doses in particular treatments were different. In maize grain from the following treatments: KN, NPK, NK+P1 and NK + P2, the phosphorus content was 5.717 to 5.952 g P kg^{-1} d.m. in grain and from 3.799 to 4.535 g P kg^{-1} d.m. in straw. In contrast, a significant increase in the phosphorus content was observed in grain (7.060 g P kg^{-1} d.m.) from the treatment with the highest dose of this element applied in the form of ash. The excess of P versus the NPK treatment was 33.0% in grain and 6.18%. in straw. Similar phosphorus concentrations in maize grain and straw from the treatments unfertilized with this element or from the treatments fertilized with its lower doses might have resulted form the high richness of soil in the experimental field in assimilable phosphorus.

The same dose of potassium (91.30 kg K ha^{-1}) in the form of potassium salt was applied to all the experimental treatments. However, an additional dose of potassium was added (from 6.74 to 20.22 kg K ha^{-1} over three years) to the variants of fertilization with municipal sewage sludge combustion ash, which did not reflect itself in the content of K in maize grain (average 4.436 ± 0.402 g K kg^{-1} d.m.) or straw (average 12.26 ± 0.260 g K kg^{-1} d.m.) – Table 4. Although the highest content of potassium was found in maize grain from NK + P3 treatment (5.055 g K kg^{-1} d.m.) and straw (12.51 g K kg^{-1} d.m.), compared to the treatments without additional potassium (NK and NPK) the differences seem small. It may be concluded that maize was well-nourished with potassium, which – according to Szczepaniak et al. (2014) – determined the volume of maize yields.

The weighted average of the calcium content in maize grain was 0.628 ± 0.070 g Ca kg^{-1} d.m., being over 16-fold higher maize straw (10.479 ± 1.036 g Ca kg^{-1} d.m.). The highest calcium content in grain (0.732 g Ca kg^{-1} d.m.) was determined in the treatment with the highest dose of ash, in contrast to straw, which had the highest calcium content (11.94 g Ca kg^{-1} d.m.) in the treatment with the lowest ash dose. The content of calcium was 9.9 to 33.8% higher in straw from the treatments with NPK and NK + ash than from the NK treatment. Such dependencies could have resulted from the annual use of calcium with enriched superphosphate and ash from municipal sewage sludge combustion.

Similarly to calcium, the weighted average content of magnesium in maize grain (0.994 g Mg kg^{-1} d.m.) was lower than in straw (3.509 ± 0.180 g Mg kg^{-1} d.m.). Despite the contribution of magnesium in the variants with ash (from 6.21 to 18.63 kg Mg ha^{-1} over three years), no significant influence on its content in maize grain and straw was observed.

The content of macroelements in maize as well as in other plants is dependent on many factors, including the climate, soil or variety. Gąsiorowska et al. (2011) analyzed the chemical composition of grain from four maize varieties and found a lower average content of phosphorus (2.010 g P kg^{-1} d.m.), potassium (1.980 g K kg^{-1} d.m.) and calcium (0.300 g Ca kg^{-1} d.m.) than herein, while the magnesium content (1.170 g Mg kg^{-1} d.m.) was slightly higher than in the present research. Skowrońska and Filipek (2009) determined more phosphorus (average 5.800 g P kg^{-1} d.m) than the former authors, in which their results resembled our determinations. Data given by Li et al. (2012) indicates a high diversity of the phosphorus content (from 2.300 to 7.500 g P kg^{-1} d.m) in maize grain. Compared to the current experiment, Baran et al. (2011) examined the influence of varieties and fertilization regimes on the content of macroelements in maize grain and straw, noting a similar content of magnesium in grain (1.140 g Mg kg^{-1} d.m.), a much lower Mg content in straw (1.910 g Mg kg^{-1} d.m.) and less phosphorus and calcium in both maize organs. The content of potassium in the research by Baran et al. (2011) was very high, i.e. 15.23 g in grain and 8.260 g K kg^{-1} d.m. in straw, while normally there is more potassium in straw than in grain.

In both maize grain and maize straw from the individual fertilization treatments, the average content of sulphur (Table 4) was not much varied: 1.015±0.057 g and 0.899±0.085 g S kg^{-1} d.m., repectively. Slight variations of the sulphur content in maize grain and straw from the fertilization treatments are the result of using equivalent doses of this element in the form of ammonium sulphate, which incorporated into soil 48 kg S ha^{-1} annually. Another reason is the small amount of sulphur, which originated from enriched superphosphate (2.5 kg S ha^{-1}) applied to the NPK treatment. The average content of sulphur in maize grain reached a similar level (1.010 g S kg^{-1} d.m.) as in the research by Barczak et al. (2011), but higher than the average content (0.826 g S kg^{-1} d.m.) reported by Filipek-Mazur et al. (2013).

In addition to the levels of elements, ionic proportions of macroelements play a very important role in yield quality (Table 5). This research shows the N:S weight ratio between and, having calculated K^{+}, Ca^{2+} and Mg^{2+} ions to equivalent weights, ionic equivalent K:Mg, K:(Ca + Mg), K:Ca and Ca:Mg ratios. The weight ratio of nitrogen to sulphur (N:S) in maize grain ranged from 11.87 to 14.23, on average 13.53. A slightly lower value (N:S 12.3) was reported by Barczak et al. (2011) in an experiment on the influence of soil type and sulphur fertilization on the volume and quality of maize grain yield, in which less nitrogen in grain was accumulated then than in the pres-

Table 5

Weight ratios and ionic macroelements in maize grain

Treatments	N:S*	K:Ca**	K:Mg**	K: (Ca+Mg) **	Ca:Mg**
NK	14.23	3.509	1.469	1.036	0.419
NPK	13.61	3.823	1.331	0.987	0.348
NK+P1	11.87	3.953	1.319	0.989	0.334
NK+P2	13.74	3.346	1.232	0.900	0.368
NK+P3	14.21	3.544	1.510	1.059	0.426
Average	13.53	3.635	1.372	0.994	0.379
Standard Deviation	0.767	0.222	0.103	0.055	0.037

* weight ratios; ** equivalent ratios

ent research. According to Blake-Kalff et al. (2003), an optimal N:S ratio should range from 10 to 15:1, depending on a maize variety.

It is generally known that monocotyledonous plants readily take up potassium, which promotes the accumulation of this element in plants, especially in vegetative parts. This is known as 'luxurious consumption', and causes an imbalance between potassium and important divalent cations, magnesium and calcium. In our study, the average value of the K:Mg ratio in maize grain did not vary widely (1.232 to 1.510). Similarly, the K:(Ca + Mg) ratio in grain was not very high (0.900 to 1.059, with the average value of 0.994±0.055). The K:Ca ratio in maize grain was higher (3.635 on average), but analogously to the previously discussed proportions, its variation in the individual fertilization treatments was low, as it ranged from 3.346 to 3.953 (SD = 0.222). The Ca:Mg ratio in grain varied from 0.334 to 0.419, and 0.379 ± 0.037 on average.

In an assessment of the plant feeding value, the following ionic ratios are considered to be desirable: K:Mg = 2-6; K:(Ca + Mg) = 1.62-2.20; K:Ca = 2-4 and Ca:Mg = 1-3. Among the analyzed cation rations in maize grain, the K:Ca ratio can be distinguished as the most optimal one, while and the K:Mg and K:(Ca + Mg) are close to their optimal values. Similar values of ionic ratios in maize grain cultivated on different types of soil and with diferentiation sulphur fertilization were obtained by Murawska et al. (2013).

A simplified balance of nutrients was calculated (Table 6) on the basis of the weighted average of the nitrogen, phosphorus and sulphur content and the average yield of maize grain and straw from the three years of research, as well as the quantities of nutrients applied yearly with mineral fertilizers and ash from municipal sewage sludge combustion. The elements (N, P and S) which were applied annually in equal amounts in the particular fertilization treatments, were chosen to make a midyear balance. The negative average value of the nitrogen balance was very high: -151.5 kg ha^{-1}. A similar nitrogen balance value (-140 kg N ha^{-1}), using the same dose of nitrogen (80 kg N ha^{-1}) as in the present research, was received by Potarzycki (2009)

Table 6

The simplified balance of macroelements in soil (kg ha^{-1})

Treatments	Quantity macroelements brought to soil			Cash macroelements			Balance		
	N	P	S	N	P	S	N	P	S
NK	80	0	48	230.1	100.9	19.06	-150.1	-100.9	28.94
NPK	80	21.80	50.5	223.1	101.6	18.75	-143.1	-80.80	31.75
NK+P1	80	21.80	48.0	238.8	108.9	21.34	-158.8	-87.10	26.66
NK+P2	80	43.60	48.0	225.2	105.6	19.42	-145.2	-62.00	28.58
NK+P3	80	65.40	48.0	240.2	129.7	21.32	-160.2	-64.30	26.68
Average	80	30.52	48.5	231.5	109.3	19.98	-151.5	-78.82	28.52

from an experiment on maize. A negative balance of nitrogen should be taken into account when fertilizing plants, especially maize grown for straw, e.g. for energy purposes. Much phosphorus (109.3 kg P ha^{-1} on average) was removed with maize yield, as the P concentration was high in both grain and straw. Only the highest dose of phosphorus used in the form of ash (65.40 kg P ha^{-1}) covered approximately 50% of the maize fertilization needs. According to Grzebisz et al. (2003), out of the crops grown in a moderate climate, maize shows the stronget response to phosphorus, which might result in a significant depletion of this element in soil. The balance of sulphur was positive in every fertilization treatment, with the average value around 59% of the sulphur applied yearly with ammonium sulphate and enriched superphosphate.

CONSLUSIONS

1. Favourable atmospheric conditions in all the years of the research promoted a high yield of maize grain and maize straw.

2. In each year as well as in the whole three-years experiment, the average grain and straw yield did not vary widely between the treatments fertilized with mineral fertilizers (NK and NPK) or mineral fertilizers with addition of ash from municipal sewage sludge combustion.

3. The average content of N, P, K, Ca, Mg and S in maize grain and straw was slightly varied. Only the highest dose of ash from sewage combustion increased the average content of total phosphorus in grain by 33.0%, and in straw by 6.18%, as well as calcium in grain by 33.6%, compared with the NPK treatment.

4. In respect of the feed value, an optimal weight ratio between N:S and ion-equivalent K:Ca, as well as nearly optimal one for K:Mg and K:(Ca + Mg) were found in maize grain.

5. On average, much more nitrogen and phosphorus were removed annually with the yield of maize grain and straw than supplied with mineral fertilizers and ash. In the case of sulphur, the simplified balance was positive.

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