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Thermal conversion of granules from feathers, meat and bone meal and poultry litter to ash with fertilizing properties

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Recently, the increased consumption of poultry meat in the EU has been observed. Short cycle of poultry meat production allows adjusting the level of production to demand. With the increase in the meat production the amount of generated waste that has to be disposed because they pose a risk to the environment also increases. The work presents the possibility to produce a mixture of feathers, meat-bone meal and poultry litter that can be used for energy purposes (alternative fuel). Moreover, the composition of the ashes after combustion will be similar to phosphorus-potassium fertilizers offered for sale. The resulting granules are characterized by a calorific value in the range 13.1–13.3 kJg^{-1}. The ash after its combustion contained 11.33–13.38% of phosphorous, 4.94–5.67% of potassium, 31.85–32.69% of calcium and 2.07–2.51% of magnesium. Moreover, the ash contained 0.45–0.46% of iron, 0.10–0.11% of manganese, 0.11–0.14 of zinc and 0.02% of copper. Mineral combusted residue of this type of granules has a low content of heavy metals and can be used as an additive to fertilizers and soil improvers, in order to enrich their composition in valuable macro- and micronutrients.

Key words: granules, fertilizers, waste, combustion

Introduction

Economic development results in an increased demand for agricultural products and livestock farming. Short poultry production cycle enables continuous adaptation of production to demand, making this type of industry an important area of agricultural production. Consumption of poultry meat (broilers, turkeys, ducks) is increasing from year to year, resulting in an increase in its production. In the European Union about 45 million tons of meat in 2011 was produced. At that time, Poland took the fourth place in terms of the production of poultry and pork meat, and was also the seventh producer of beef (Staroń et al. 2016). Currently Poland ranks first in the production of poultry meat in the European Union (Eurostat 2016). In the production of poultry sector, products and waste are generated, which contributes to pollution. The main waste products are feathers and poultry litter.

Waste feathers are the main waste formed during production of poultry (Kim et al. 2001). Feathers consist of 90% keratin and constitute 5–7% of the total weight of adult chickens (Suntornsuk and Suntornsuk 2003, Costa et al. 2012, Paul et al. 2013). Feathers are discarded in the process of poultry processing and as a waste product contributes to environmental pollution (Grazziotin et al. 2006, Vasileva-Tonkova et al. 2009, Staroń et al. 2013). The development of the poultry industry in the world has led to the generation of more than 4 million tons of waste feathers each year, half of which is formed in the United States. An average size farm in Poland generates about 7 tons of chicken feathers during the year. Annually in Poland 77000 tons of waste is generated (Martinez-Hernandez et al. 2007, Górecki et al. 2010, Korniłłowicz-Kowalska and Bohacz 2010, Zaghloul et al. 2011).

Meat-bone meal (MBM) is produced from non-edible animal products falling within category III of waste (i.e. Low-risk). These include skin, fur, feathers, horns, hooves, claws, blood and meat and returns of meat products. The typical feedstock for producing MBM consists of 40% moisture, 20% fat and the remaining 40% is itself rendered to MBM. These ratios are however, quite variable. The raw material is sterilized after pretreatment (removal of metallic parts, grinding, mixing) for 30 min at 133 °C under a pressure of 0.3 MPa. Sterilized product is fed to the dryer, where the moisture evaporation and separation of the fat take place. The remaining part of the fat is secreted on a filter press at a pressure of 1 MPa, at a temperature of 90–100 °C. Solid fraction is crushed and sieved (EC 2009, Moutinho et al. 2017).

Poultry litter is mainly bird droppings, litter and small amounts of feathers and feed. One hen produces about 170–175 g of litter per day, with 20–25% dry matter. Its composition depends on factors such as changes in the weight of the bird, the type of feed, the amount of given water or productivity of poultry. It is a 62–64 kg of litter produced by one bird on an annual basis. Poultry litter is widely regarded as a natural product that can be used as a fertilizer.

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It has nutrients essential for plant growth, such as nitrogen, phosphorus and potassium, and a plurality of micronutrients. They are both in the form of organic and inorganic compounds. Nitrogen occurring in organic compounds is more stable than in the case of nitrogen occurring in mineral fertilizers. Application of poultry litter in fertilizer is associated with the odor substances which are released during the storage of litter and during the farmland fertilization (Badri et al. 2002, Kelleher et al. 2002, Schröder 2005).

Previous works were focused on application of meat and bone meal as a component of mixtures. McDonnell et al. (2001) obtained pellets from the meat and bone meal and peat, which were combusted in fluidised bed combustor. Skodras et al. (2007) prepared mixtures of meat bone meal and Greek brown coal. They studied the properties of obtained compounds under both pyrolysis and combustion conditions. Kwiatkowski et al. (2013) studied the production of energy from fixed-bed gasification of poultry feathers on an industrial scale. The process was carried out in two stages, the feathers were gasified, and the resulting gas was burned in a separate chamber. The resulting exhaust gases produce steam in the boiler. Junga et al. (2017) presented in their work the possibility of using chicken manure as fuel, burned separately and with bituminous coal. Hussein et al. (2017) used the pyrolysis and gasification of chicken manure using different gasifying media in a laboratory scale using semi-batch reactor in a temperature range of 600 to 1000 °C. Fryda et al. (2006) studied the co-combustion of meat-and-bone meal together with three fuels in a laboratory scale fluidized bed. They used two types of coal and olive bagasse residues.

The aim of the study was to analyze, determine the composition and physico-chemical properties of the granules made from feathers, meat-bone meal and poultry litter. In order to verify the possibility of their use as an alternative energy source and the possibility of using mineral residues after burning as additives to fertilizers and soil improvers designed to enrich them with the necessary elements.

Material and methods

Waste feathers (F) and poultry litter (PL) from the poultry plant (broiler farm) and meat-bone meal (MBM) produced in rendering plants were raw materials to obtain granules. Factories are located in the Wielkopolska region (Poland). Properties of raw material are shown in Table 1.

Table 1. Content of carbon (C), hydrogen (H), nitrogen (N) elements (in dry matter) and moisture of the test material

Elemental analysis (%)	Feathers	Meat and bone meal	Poultry litter
C	48.21	41.30	31.94
H	7.41	6.24	4.60
N	13.73	8.30	2.99
Moisture content (%)	54.6	4.2	13.4

Granulate which is a mixture of feathers, meat-bone meal and poultry litter was studied. Granulate can be used as a source of thermal energy and the resulting ash after burning has a composition that allows to use it for the purpose of fertilizer.

Research aimed at the development of the most preferred composition of granulate consisting of two or three components, which would be characterized by high calorific value, and the high contents of macro- and micronutrients. The two-component system of granulate contained feathers and meat-bone meal or feathers and poultry litter, and ternary system contained feathers, meat-bone meal and poultry litter. An experiment plan for the mixtures was used for the selection of the most favorable composition of mixtures (StatSoft, Inc. 2013). The relative desirability of different output values determines the usability function. The utility values of the dependent variable can vary for a value predicted from 0.0 (undesired) to 1.0 (highly desirable). Experiment plan consisted of a complete plan (the content of all the raw materials from 0 to 100%) and plans with restrictions (feathers content was in one case, min 40% in the second min 50%).

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Simplex-centroid plan belonging to the plans for the mixtures allows restricting the size of the input. Then the plan is created in subdomain (simplex) defined by the constraints.

Matching the response surface to the results was based on the selected model having the form:

$$y = b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + d_{12}x_1x_2(x_1 - x_2) + d_{13}x_1x_3(x_1 - x_3) + d_{23}x_2x_3(x_2 - x_3) + b_{123}x_1x_2x_3$$

where:

y – approximated values of output quantities,

$b_1, b_2, b_3, \cdots, b_{123}, d_{12}, d_{13}, d_{23}$ – predictors of the regression coefficients,

x_1, x_2, x_3 – approximated values of input quantities.

Mixtures were prepared from raw materials in the operating state (in state of delivering from the plant). Calorific value, total phosphorus content and other macronutrients in the resulting ash after combustion were the dependent variables characterizing the composition of the granulate.

The results of the analysis (Table 1), which did not have a normal distribution, were normalized by appropriate using mathematical transformations (Mazerski 2000). The data are presented in normalized scale which is helpful when comprising values of variables which do not have normal distribution. Formulas based on which normalized values were calculated are presented in approximation profiles with utility function (Fig. 2).

Granulate was obtained from two- and tree-component mixtures, using a manual tablet press and had defined composition. The resulting granulate were tested for determining the heat of combustion using calorimeter KL-12Mn Precyzja-Bit Company (Polish Norm 1981). It was then combusted in a stationary electric furnace at 900 °C for 3 h. Ashes were analyzed in order to determine the elemental composition (using ICP-OES spectrometer), and in addition there was a specified spectrophotometric method for total phosphorus content (Pc). Total phosphorus content (Pc) was determined using a spectrophotometer Nanocolor UV/VIS Macherey-Nagel at a wavelength of 430 nm. In order to determine the total phosphorus in samples, probes were mineralized in a mixture of concentrated acids: nitric acid and hydrochloric acid (3:1) at reflux (Polish Norm 1988). ICP-OES served to analyze the elemental composition of ashes. It was done using the emission spectrometer with inductively coupled plasma OPTIMA 7300 DV by PerkinElmer. The tested materials, approximately 0.2 g, were mineralized using concentrated acids: hydrofluoric (HF), nitric (V) (HNO_3) and chloric (VII) ($HClO_4$) at the boiling point. The first stage of mineralization was carried out with 4 cm^3 of HF. After evaporation of acid, 8 cm^3 of mixture of HNO_3 and $HClO_4$ (1:1) were added. The last step of mineralization was the addition of 4 cm^3 of HNO_3 and filtering the solution to flasks and diluted to 50 cm^3. Obtained solutions were again respectively diluted to ICP analyze. Results are the mean of triplicates.

The results were subjected to statistical analysis. The resulting equations of the research were visualized in layer-graphs in a triangular coordinate system.

Results

In order to compare the composition of the resulting ash to the composition of phosphorus-potassium fertilizers offered for sale, the content of elements in the ash (phosphorus, potassium, calcium and magnesium) was analyzed. Phosphorus-potassium fertilizers offered for sale differ in composition depending on the manufacturer and application. The nutrient content varies in the range: 12–20% P_2O_5, 13–25% K_2O, 5–13% CaO and 4–15% MgO.

The values of the independent variables and the results of the analysis are summarized in Table 2.

Figure 1 shows a graphical representation of the object of research.

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Table 2. The composition of the mixtures, calorific value, content of macro- and micronutrients in the resulting ashes

Sample No.	Mixture composition (mass fraction, w)			Heat of combustion J g^{-1}	Elemental composition of ash (%)							
	F	MBMM	PL	Q	Pc	K	Ca	Mg	Fe	Cu	Mn	Zn
1	1.00	0.00	0.00	13160	17.03	9.40	16.41	3.01	0.662	0.073	0.270	0.766
2	0.00	1.00	0.00	17161	16.97	1.02	35.14	0.80	0.429	0.004	0.009	0.039
3	0.00	0.00	1.00	11799	8.14	6.84	34.38	3.09	0.472	0.013	0.141	0.023
4	0.50	0.50	0.00	14632	16.01	2.30	33.35	1.10	0.455	0.014	0.043	0.143
5	0.50	0.00	0.50	13014	8.86	7.40	32.10	3.10	0.486	0.022	0.162	0.133
6	0.00	0.50	0.50	14542	12.72	4.15	34.36	2.02	0.453	0.009	0.076	0.032
7	0.67	0.17	0.17	12713	13.29	5.63	30.58	2.18	0.480	0.024	0.122	0.225
8	0.17	0.67	0.17	15875	14.94	2.56	34.32	1.27	0.439	0.008	0.041	0.061
9	0.17	0.17	0.67	12991	10.42	6.09	34.17	2.64	0.451	0.012	0.114	0.050
10	0.33	0.33	0.33	14533	12.98	4.64	32.22	2.11	0.442	0.014	0.088	0.091
11	0.50	0.25	0.25	13306	12.78	5.07	32.51	2.11	0.456	0.018	0.101	0.136
12	1.00	0.00	0.00	13160	16.34	9.49	16.09	3.00	0.623	0.074	0.271	0.814
13	0.75	0.00	0.25	12808	11.55	7.87	28.93	3.10	0.520	0.031	0.177	0.265
14	0.75	0.25	0.00	13000	17.44	3.78	28.48	1.50	0.497	0.026	0.095	0.279
15	0.67	0.17	0.17	12713	13.02	5.63	29.51	2.27	0.480	0.025	0.117	0.227
16	0.50	0.50	0.00	14632	16.01	2.31	33.14	1.11	0.455	0.014	0.046	0.138
17	0.50	0.00	0.50	13014	8.86	7.55	32.41	3.17	0.487	0.020	0.151	0.128
18	0.40	0.60	0.00	15531	17.17	1.96	35.00	1.01	0.449	0.011	0.034	0.110
19	0.60	0.20	0.20	12211	13.72	5.25	31.68	2.15	0.501	0.020	0.107	0.186
20	1.00	0.00	0.00	13160	16.51	9.30	16.25	3.19	0.643	0.073	0.250	0.758
21	0.70	0.00	0.30	11981	9.98	7.91	29.20	3.16	0.503	0.028	0.179	0.245
22	0.40	0.30	0.30	13274	13.48	4.73	32.46	2.12	0.449	0.015	0.091	0.102
23	0.70	0.30	0.00	13163	17.25	3.30	29.21	1.48	0.493	0.024	0.076	0.243
24	0.40	0.00	0.60	12257	9.09	7.14	31.49	3.16	0.500	0.019	0.152	0.101

F = feathers; MBM = meat and bone meal; PL = Poultry litter; Pc = total phosphorus content

The presented approximation profile characterizes the system with 50% share of the mass of feathers and 25% of the mass fraction of meat and bone meal and 25% of the mass fraction of poultry litter. This mixture is characterized by the combustion heat of 13.1 kJg^{-1}, and the ash after its combustion contains: 13.38% of phosphorus, 4.94% of potassium, 31.85% of calcium and 2.07% of magnesium. Converting elemental content of macronutrients to oxide forms, the ash contains: 30.65% of P_2O_5, 9.5% of K_2O, 44.56% of CaO and 3.43% of MgO. The ash comprises also: 0.46% of Fe, 0.02% of Cu, 0.10% of Mn and 0.14% of Zn.

The ash formed after combustion of mentioned system has a higher content of phosphorus and calcium and less potassium and magnesium, comparing available fertilizer. In order to enrich the resulting ash in potassium and magnesium the fraction of MBM should be reduced by increasing the fraction of poultry litter in the mixture.

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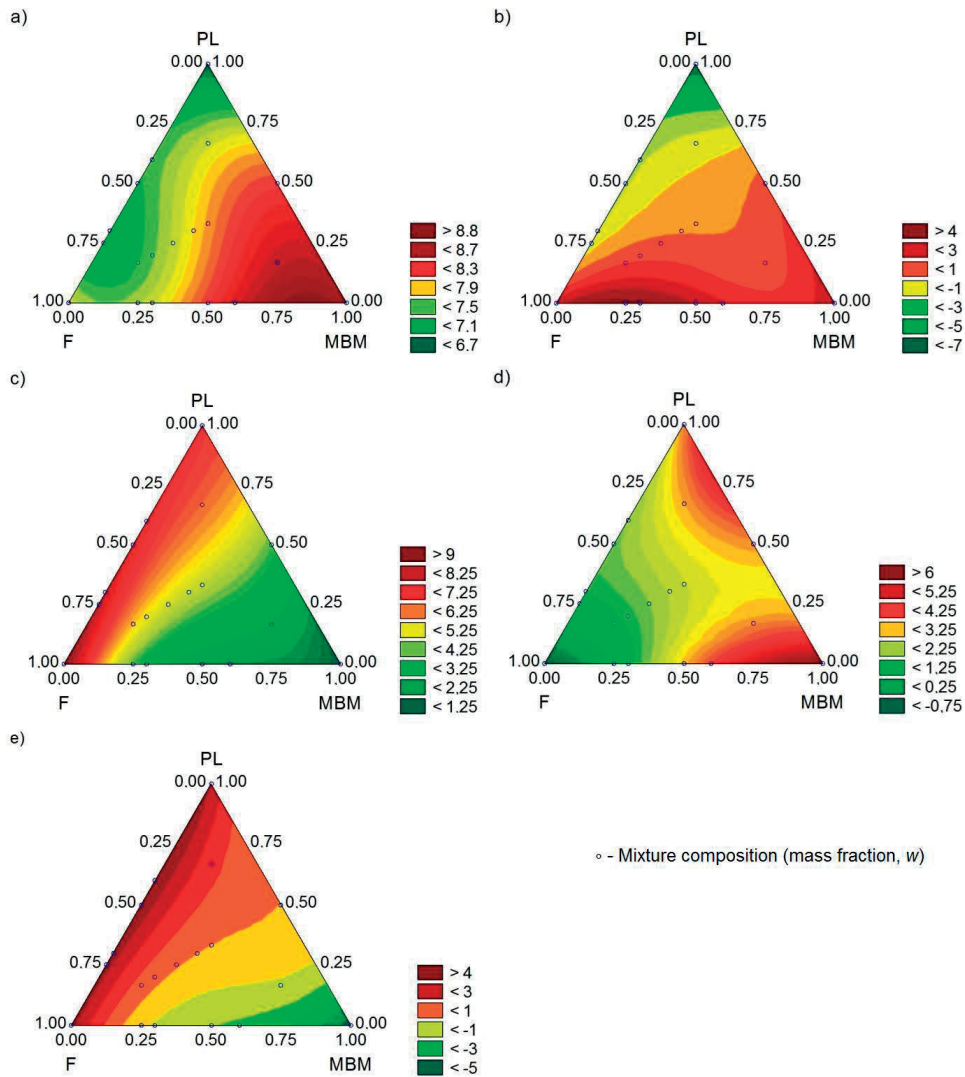
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Fig. 1. Graphical presentation of the function tested object: a) the calorific value, b) content of Pc (total phosphorus content), c) content of K, d) content of Ca, e) content of Mg

Basing on model parameters, an approximation profile was obtained which is shown in Figure 2. Mixture (40% of feathers, 25% of MBM and 35% of poultry litter) is characterized by the combustion heat equal to 13.3 kJg^{-1}, and the ash after its combustion contains: 11.98% of phosphorus (P_2O_5 27.45%), 5.23% of potassium (6.30% K_2O), 32.66% of calcium (CaO 45.69%) and 2.25% of magnesium (3.73% MgO). Moreover, the ash contains 0.45% of iron, 0.02% of copper, 0.10% of manganese and 0.11% of zinc.

Reducing the amount of feathers in a mixture of 10% and increasing the fraction of poultry litter (40% of feather, 25% of MBM and 35% of poultry litter) resulted, the reduction of phosphorus content (about 3% of P_2O_5) and a simultaneous increase in the potassium (0.35% K_2O), magnesium (0.3% MgO) and calcium (CaO 1.13%) content, which agreed with previous findings.

Using a mixture having a composition of 40% F, 20% of MBM and 40% of PL, calorific value is 13.1 kJg^{-1}. Ashes after combustion contain: 11.33% of phosphorus (25.96% P_2O_5) 5.67% potassium (6.83% K_2O), 32.69% of calcium (45.73% CaO) and 2.51% magnesium (4.16% MgO). They also contain 0.46% of iron, 0.02% of copper, 0.11% of manganese and 0.11% of zinc.

Using the 40% content of feathers in the mixture and reducing the content of MBM from 25% to 20% and increasing the fraction of poultry litter from 35 to 40% gives a mixture of reduced phosphorus content (about 4.7% P_2O_5), high calcium (more than 1% CaO), potassium (about 0.9% K_2O), and magnesium (0.73% MgO) content.

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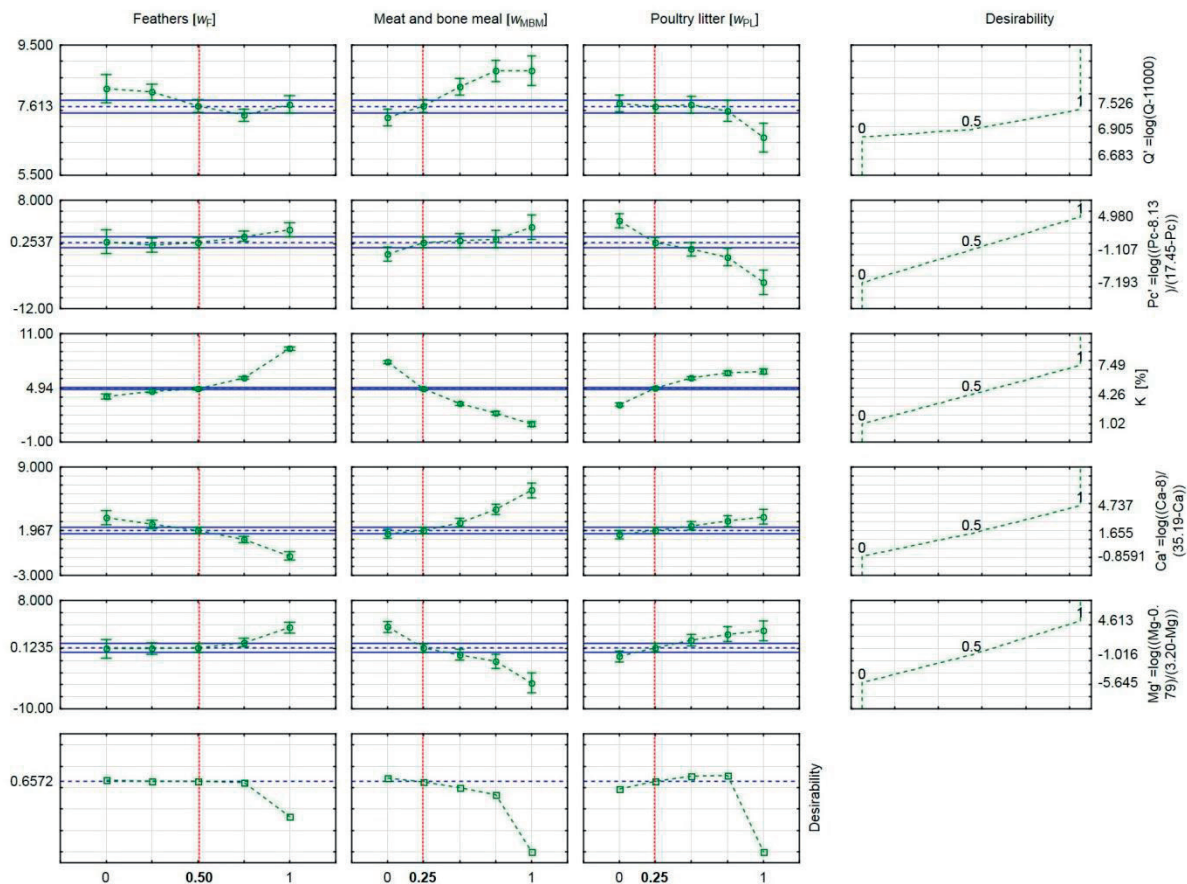
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Fig. 2. Approximation profile with the utility function for the mixture F:MBM:PL – 0.50:0.25:0.25

Discussion

Calorific value increases with increasing mass fraction of meat-bone meal. This is due to the fact that meat-bone meal (because of their organic origin) has the highest heat of combustion (Conesa et al. 2005). A high content of phosphorus in ash is observed with a smaller share of poultry litter in the mixture (due to low P content of poultry litter compared to feathers and MBM). Ash after combustion of meat-bone meal contains nearly exclusively hydroxyapatite, which consists in a significant amount of phosphorus and calcium (Fryda et al. 2007). For this reason, meat-bone meal is a rich source of these macronutrients. Brod et al. (2016) reported that phosphorus from hydroxyapatite and chlorfluorapatite has low solubility, especially in soils with pH >6.5.

Calcium in the ash also origins from poultry litter, it is in the form of calcium carbonate and calcium oxide. In the ash after combustion of poultry litter and feathers, a high level of potassium and magnesium is observed (Kelleher et al. 2002, Abelha et al. 2003). Poultry litter and waste feathers can be used as a major source of these elements.

Ash after thermal conversion of the mixtures of feathers - MBM - poultry litter has a composition of macro- and micronutrients composition comparable with of calcium and phosphorus-potassium fertilizers, and phosphorus present is characterized by high absorption by plants. In case of using the ashes for fertilizers, an important parameter is not only the amount of nutrients in ashes but also theirs solubility in a soil which determines plant-availability. Previous studies (Staroń et al. 2016) have shown that the solubility of phosphorus in citric acid varies from about 40 to more than 90% and depends on the type of waste and the combustion temperature of those waste.

MBM is a material which composition depends on the raw material used. However, it always contains significant volatiles and ash content rich in alkali and alkaline earth metals. Besides calcium and phosphorus there is also chlorine. In MBM combustion and co-combustion studies, the severe corrosion and fouling problems were attributed to chlorine. The use of chicken manure as an additional ingredient that contains significant amounts of Ca causes the melting temperature to change to a higher level, thereby decreasing the sintering and agglomeration problems that arise from the combination of K, Cl, P with Si and S. This problem occurs in the case of i.a. use of straw as a fuel for co-incineration (Fryda et al. 2006). During research conducted by McDonnell et al. (2001) it

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was found that co-combustion of MBM in pelletised form with some peat reduced the associated with the fuel volatility. Olofsson et al. (2002) observed a reduction of NO and NOx emissions by adding MBM to coal because of its high volatile content.

Conclusion

Calorific value of obtained granules from feathers, meat-bone meal and poultry litter can be used as an alternative source of energy. In addition, ash after combustion is a rich source of calcium, phosphorus and potassium and has a high content of trace elements (Zn, Cu, Mn, and Fe). Therefore, they may be used as additives for fertilizers and soil improvers in order to improve the physical and chemical properties of the soil. The nutrient content in the ash obtained from the plants is similar to that of the phosphorus-potassium fertilizers offered for sale. However, the solubility of nutrients in ashes it varies according to the type of waste from which the ash was formed and the pH of the soil. The ash formed as a result of controlled burning is also safe in terms of sanitation, which is a basic requirement for the waste and animal by-products used for commercial purposes.

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