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IMPACT OF AEROBIC BIOSTABILISATION AND BIODRYING PROCESS OF MUNICIPAL SOLID WASTE ON MINIMISATION OF WASTE DEPOSITED IN LANDFILLS

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The article discusses an innovative system used for aerobic biostabilisation and biological drying of solid municipal waste. A mechanical–biological process (MBT) of municipal solid waste (MSW) treatment were carried out and monitored in 5 bioreactors. A two-stage biological treatment process has been used in the investigation. In the first step an undersize fraction was subjected to the biological stabilisation for a period of 14 days as a result of which there was a decrease of loss on ignition, but not sufficient to fulfill the requirements of MBT technology. In the second stage of a biological treatment has been applied 7-days intensive bio-drying of MSW using sustained high temperatures in bioreactor. The article presents the results of the chemical composition analysis of the undersize fraction and waste after biological drying, and also the results of temperature changes, pH ratio, loss on ignition, moisture content, combustible and volatile matter content, heat of combustion and calorific value of wastes. The mass balance of the MBT of MSW with using the innovative aeration system showed that only 14.5% of waste need to be landfilled, 61.5% could be used for thermal treatment, and nearly 19% being lost in the process as CO_2 and H_2O.

Key words: municipal solid waste, biostabilisation, biodrying

1. INTRODUCTION

Mechanical-biological waste treatment plants integrate mechanical (grinding, separation, screening, pneumatic classification, etc.) and biological processes (occurring under aerobic and anaerobic conditions). MBT systems are used in a treatment of municipal solid waste (MSW) for reducing the amount of waste going to landfill. Biological methods of processing biodegradable municipal waste are also used to reduce microbial activity, reduce CO_2 and CH_4 in the case of storage and landfilling, as well as to produce alternative fuels (Adani et al., 2002, 2004; Dębicka et al., 2013; Flamme, 2006; Mohn et al., 2008; Sugni et al., 2005; Titta et al., 2007; Velis et al., 2009). Yasuhura et al. (2010) and Tambore et al. (2011) also point to an increase in safety of life and health of people working in the waste disposal buildings and installations where post-MBT waste is deposited. Currently, the most popular biological waste treatment processes include biostabilisation and biodrying. These processes involve self-heating (autothermally) of

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the waste mass using heat released during the decomposition of organic matter. As such, they represent an interesting alternative for waste management from the economic point of view (Domińczyk et al., 2012). The mechanical – biological treatment processes of municipal waste are particularly popular in Europe, which is associated with the European Union's policy (2008/98/EC, 99/31/EC) concerning the processing of mixed municipal waste, including the regulations regarding the disposal of biodegradable waste (Abeliotis et al., 2012; Binner, 2003; Dębicka et al., 2013; Dias et al., 2014; Ibbetson, 2006; Kuehl-Weidemeier, 2007, Pires et al., 2007; Steiner, 2005, 2006). The two above-mentioned directives indicate the necessity of dealing with waste in accordance with a proper hierarchy, which in the first place lists prevention/reduction, next reuse and recycling (i.e. mechanical and biological), recovery in the form of energy and finally landfilling as the least desirable method of waste treatment (Garg et al., 2009; The Landfill Directive 1999/31/EC).

In MBT plants, as a result of the process of mechanical separation of the stream of municipal waste most often using drum screens (with various mesh size from 50 to 100 mm, at least 80 mm in Poland), two fractions are separated – undersize and oversize. The undersize fraction contains significant amounts of organic matter and is transferred to the biological treatment process. The oversize fraction is usually transferred to the energy recovery process (Dębicka et al., 2013; Jędrczak, 2008). Separation of materials fit for recycling from the waste stream is also possible (Regulation, 2012). According to the previous investigation (Malinowski, 2012), the share of separated metals, glass, paper and plastics does not exceed 7% of the mass.

This article presents the results of analyses carried out for undersize fraction before the biological treatment processes, as well as an analysis of substances obtained using subsequent processes of biostabilisation and biodrying performed in an innovative bed bioreactor. Polish standards (Regulation, 2012) state that, following the stabilisation process, waste should ripen in heaps for at least 6 weeks (in order to reach the proper parameters to consider a stabilised waste), which involves the access to a large, hardened (concrete) and top drained area. The stabilised waste is then stored as a stabilised waste fraction. Thus, the stabilisation process does not affect the overall waste minimisation. The article proposes an alternative method of biological treatment consisting in carrying out the biostabilisation process, after which the resulting waste will be subjected to the biodrying process in order to produce a stable and biologically inactive fuel from waste. This method should also allow for the minimisation of waste deposited in landfills. The process of biodrying of municipal waste and the production of alternative fuel (then burned in power plants or cement plants) is still an underrated method of thermal treatment, which guarantees significant reduction in environmental waste. Additionally, this article presents the results of analyses of using bio-dried (and re-moistened) waste to produce biogas.

The main aim of this study was to determinate influence of biostabilisation and biodrying process (carried out in special bioreactors equipped with a innovative bed) on the minimisation of waste deposited in landfills. The additional objectives of the study were to define energy and fertilising applicability of biologically treated (stabilised) waste.

2. MATERIALS AND METHODS

2.1. Plant and process parameters

The mechanical and biological waste treatment plant (MIKI Recycling Ltd.) is located in Krakow (southern Poland). The annual capacity of the plant is 40 000 Mg of mixed municipal waste (≈160 Mg per working day). After the receipt of mixed municipal waste at the plant, it passes through mechanical sorting, which separates metals, glass, plastic and paper (manually and mechanically). This waste is then additionally cleaned and sent to recycling. The remaining waste stream is subjected to separation on a rotary screen with a mesh of Ø 80 mm. As a result of this separation, the undersize fraction is produced and transferred to biological treatment. The oversize fraction is transferred to a thermal recovery. Following the biostabilisation and biodrying processes, the waste is separated into two fractions of different granularity – <20 mm and 20–80 mm. Waste is considered to be stabilised after meeting the relevant requirements (Regulation, 2012):

- loss of ignition (LOI) < 35% dry mass, and the amount of total organic carbon (TOC) < 20% d.m., or
- the loss of organic matter in processes before and after stabilisation should be higher than 40% d.m., or
- respiration Activity $RA_4 < 10$ mg $O_2 \cdot g^{-1}$ d.m.

After biological processing, waste can be deposited in a heap once reaching the following criteria (Regulation, 2013):

- loss of ignition (LOI) < 8% d.m.,
- total organic carbon (TOC) < 5% d.m.,
- heat of combustion max. 6 $MJ \cdot kg^{-1}$ d.m.

The detailed waste flow in the process is shown in Fig. 1. Percentage of waste mass shown in the figure after individual processes relates to the remains and losses after subsequent stages of processing and should be understood to mean the percentage share of initial mass of mixed municipal waste (100%).

Biological treatment process was carried out in 5 bioreactors with a total capacity of 36 m^3 and a working capacity of 31.5 m^3 (2.1 m wide, 6.5 m length and 2.3 m high). The remaining volume of the bioreactor is the space under the bed used for injecting air and collect leachates. Bioreactors are based on hook containers allowing direct loading on a special vehicle and measuring parameters such as mass loss in subsequent days of the cycle. The bioreactors were equipped with inspection windows for sampling material to laboratory testing. Humid post-process air was transported to a biological filter (one filter with a capacity of 36 m^3 per 7 bioreactors) using a 4 kW fan.

Typical bioreactors used for composting, stabilisation or biodrying utilise beds made of a plate with drilled holes of various diameters. The study presented in this article was performed in bioreactors (Fig. 2) equipped with an innovative bed as in Figs. 3 and 4. The bed consists of 6 injectors (0.05 m wide, 6.5 m long, 0.04 m high) shown in Fig. 4 along the whole width of the bottom and connected by a plate. Each injector is equipped with semi-circular holes (r = 0.025 m) on both sides. The total area of the openings in all six injectors is equal to about 7% of the total cross-sectional area of the bed. The innovate solution used in the analysis results in better distribution of air within the material being dried and stabilised, as well as reduced clogging of the holes with waste.

In the process of biostabilisation, the aeration of the material was periodical and regulated depending on the temperature of the processed waste (fan motor power 0.55 kW, maximum amount of air injected into the reactor could reach 4500 $m^3 \cdot h^{-1}$). In the biological drying process, the air was continually pumped with maximum intensity. The sub-process air was transferred to the biofilter. Studies were carried out simultaneously in 5 thermally insulated bioreactors. The average daily outdoor air temperature was in the range of 2–13°C. The process temperature was monitored automatically by means of three two-metre PT 100 probes in three different points in the bioreactor (from the top), i.e. in the central part, 2 metres from the air inlet and 2 metres from the wall of the bioreactor with an air outlet. Moreover, the ambient temperature and the temperature of the exhaust air were measured. The process control program also saved air flow data. The mass of the waste being processed in the bioreactors was measured during the process on a certified vehicle scale.

2.2. Sampling and laboratory analysis

Samples for MSW measurements of the over- and undersized fractions, as well as waste from the biological treatment process were taken according to the method recommended by the European Committee for Standardization, 2006. Characterisation of Waste – Sampling of Waste Materials – Framework for the

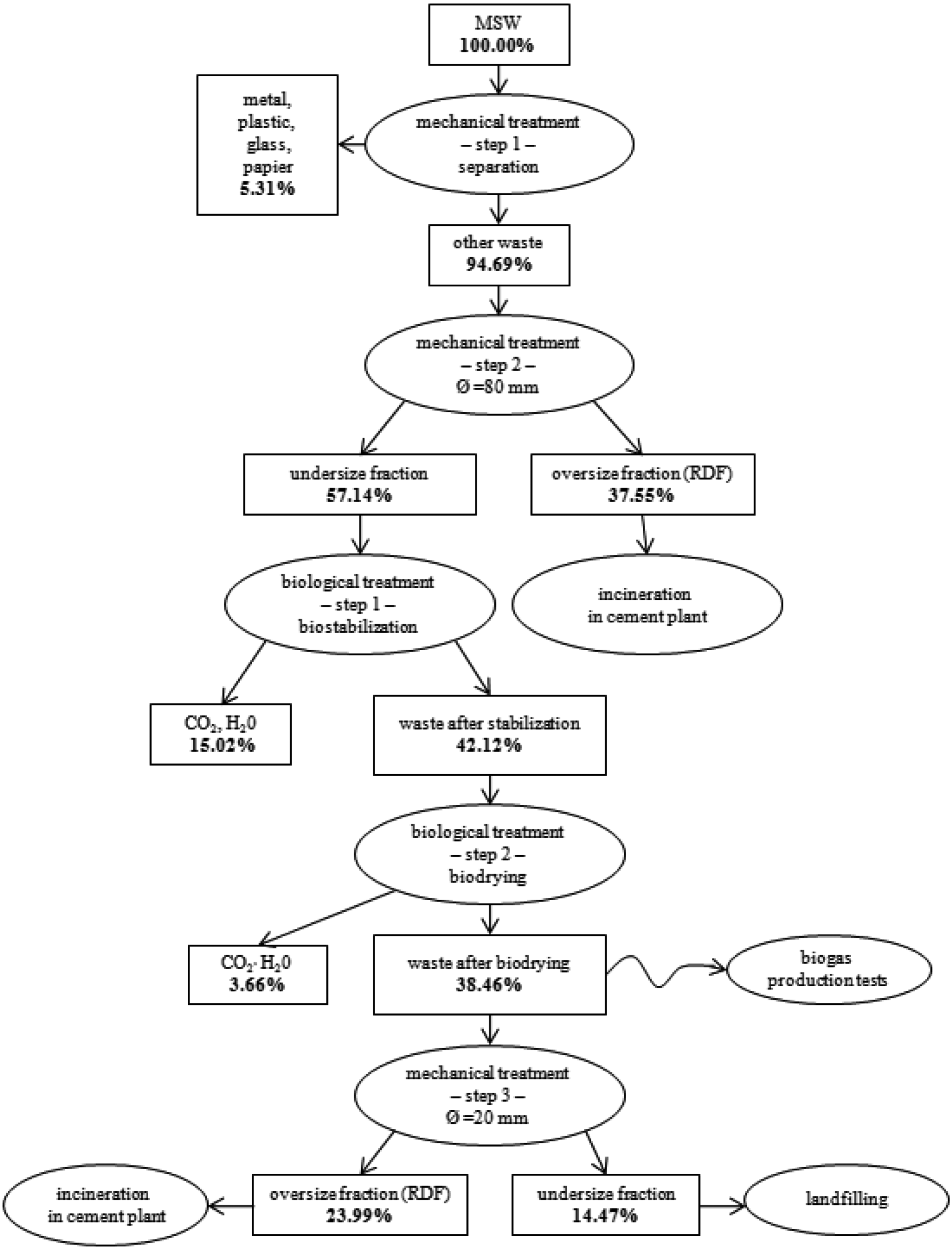

Fig. 1. Scheme of mass flow

Fig. 2. Bioreactors used in research – real view

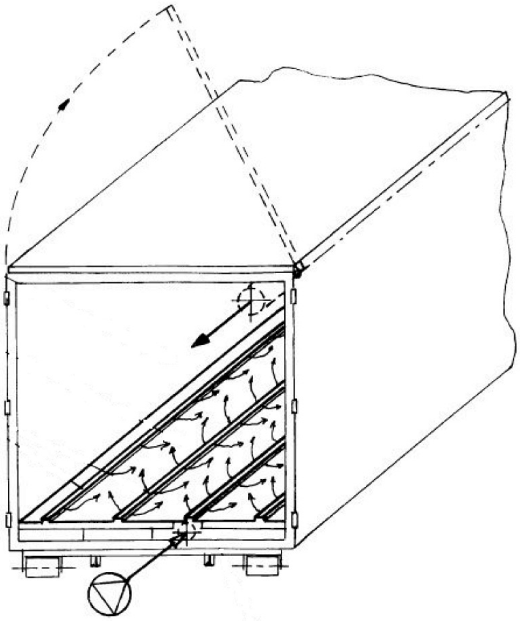

Fig. 3. Bioreactor used in research – detailed drawing, Source: Patent Application no 121933 in Polish Patent Office

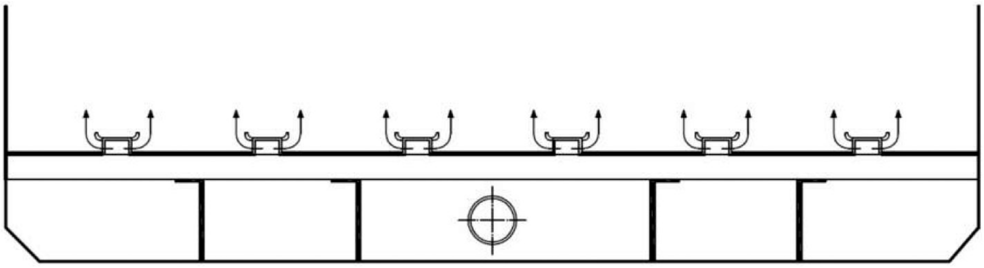

Fig. 4. Innovative bed of the bioreactor – front view of the bed, Source: Patent Application no 121933 in Polish Patent Office

Preparation and Application of a Sampling Plan (EN 2006, 14899). At the headquarters of MIKI Recycling Ltd., analyses were made of the morphological contents of the waste under treatment (mainly coming from the urban area) according to the national methodology (Jędrczak, Szpadt, 2006), taking 30 samples of approximately 100 kg each. The composition of the undersize and oversize fractions was determined for the same morphological groups as in the case of MSW, but the mass of each sample was approximately 1000 g. In relation to the national methodology a separate group of waste was isolated, namely intimate hygiene products.

In the process of analysing the morphological composition, the portion of biodegradable municipal waste was calculated as a sum of: 100% organic, 100% paper and cardboard, 50 % wood, 50% textiles, 40% multi-material waste and 30% fine fraction (<10 mm). The share of these morphological groups in biologically processed waste is very important, as it directly impacts the parameters and the course of the process. The study determined the density of the waste, its pH, as well as moisture, which were determined by weight loss in mass of dried waste at 105°C (PN-EN 14774-3:2010). The mass of each sample for drying was approximately 1000 g. Moreover, for the oversize fraction and the results of its processing, samples were analysed for their properties as fuel, which allowed to assess the usability of produced waste for energy production:

- ash content in accordance with PN-EN 14775:2010 by burning the sample in a muffle furnace at 815°C;
- volatile content according to PN-EN 15148:2010. Determination of volatile solid fuels was carried out by ignition weighted amounts taken from the analytical sample at 850°C for 7 minutes without air;
- loss on ignition was determined according to PN-EN 15169 by heating the samples in a muffle furnace at 550°C;
- combustion heat was determined by calorimetric method in accordance with PN-ISO 1928 and PN-Z 15008-04:1993. The above determination was performed on a sample with a mass of 1 ± 0.1 g placed in a bomb calorimeter in the form of a compressed pellet. Ignition of the sample was made using a kanthal wire with a diameter of 0.1 mm embedded into the pellet. The calorific value was calculated by a computer program controlling the operation of the calorimeter;
- calorific value PN-Z 15008-04:1993 – Municipal solid waste – Fuel testing Determination of the heat of combustion and calculation of net calorific value.

Table 1. Parameters of analysis method

Parameters	Wave length	Limit detection	Content in certificated material	Measured	Recovery
	[nm]	[mg·dm^{-3}]	[mg·kg^{-1}]	[mg·kg^{-1}]	[%]
Mg	285.208	0.0016	1360	1414.4	104
P	213.617	0.076	2300	2231	97
Ca	317.933	0.01	21600	22896	106
Na	589.592	0.069	500	485	97
K	766.490	–	21000	19740	94
Cd	228.802	0.0027	0.03	0.0315	105
Cr	267.707	0.0071	6.5	6.76	104
Cu	327.393	0.0097	9.4	10.058	107
Fe	238.204	0.0046	185	179.45	97
Mn	257.608	0.0014	47	46.53	99
Ni	231.604	0.015	4	3.84	96
Pb	220.353	0.042	1.6	1.696	106
Zn	206.200	0.0059	24	23.52	98

Samples of approximately 200 g of dry mass were taken from the undersize fraction and the waste generated by stabilisation of analytical samples. Laboratory samples were dried, homogenised and subjected to dry mineralisation in an open system. Samples were mineralised in a muffle furnace at 450°C and then solubilised in a solution of nitric acid (V). The analytical sample weight was 3 g of dry mass. The concentration of the analysed elements in the resulting solutions was determined by atomic emission spectrometry, using an Optima 7600 camera from Perkin Elmer. Wavelengths used to determine the concentration of the analysed elements and the limits of quantification of the methods used are given in Table 1. Certified reference material IEA-V-10 was used to control the correctness of analyses of tested elements. Table 1 includes the results of analyses of the reference material with recovery value, which was estimated based on 4 series of analyses. The aim of the study was to determine the suitability of the stabilised waste for fertilising purposes.

2.3. Potential biogas production

Dried biological waste was hydrated to a moisture content of 90% and subjected to the methane fermentation in fermentation chambers of 2 dm^3. The fermentation was static. Waste was injected with bacteria from the biogas manufacturing process taken from ensiled leaf rosettes of sugar beets. The process of methane fermentation and observations were carried out in accordance with German DIN 38414-S8 standard. Methane fermentation was accomplished within 21 days, during which the gain and composition of biogas were observed. The produced biogas was temporarily stored in a container of variable volume, from which the Nano 60 gas analyser sampled gas for analysis. Sikora (2012) states that the use of the undersize fraction or the organic fraction of MSW in the form of monosubstrate has a very low productivity of biogas (50 $Ndm^3 \cdot kg^{-1}$ s.m.). The use of such waste in co-fermentation with corn silage and cattle liquid manure results in an increased amount of biogas and may be successfully used as supplementary mass in agricultural biogas production. In addition, Adani et al. (2004) report that biologically treated (stabilised) waste may yield more biogas than the untreated organic fraction of municipal waste. The aim of this study was to determine the intensity of emission, the composition and the amount of biogas that may be yielded from waste that had been biodried and rehydrated, then injected with bacteria grown in the methane fermentation process based on sugar beet leaf rosette silage.

3. RESULTS

The first element of the MBT technology was the manual (on tables) and mechanical (magnetic separator) separation of waste with commercial value from the MSW stream from urban areas. The percentage of waste separated at the beginning of processes (metals, paper, plastic) is given in Table 2. On average, 5.32± 1.1% of the waste is separated at this stage. Malinowski (2012) writes that the mass of waste separated from the MSW stream depends primarily on the morphological composition and the time of year and is in the range of 3 to 7 %.

Table 2. The percentage of waste separated in the course of mechanical separation in relation to the total weight of the mixed waste stream

Waste group	Share [%]
Metals (ferrous and non-ferrous)	1.51 ± 0.5
Plastics and composites	2.48 ± 1.3
Glass	0.79 ± 0.4
Paper and Cardboard	0.53 ± 0.4
Total	5.32 ± 1.1

Table 3 summarises the results of the analysis of morphological composition of mixed municipal waste and the morphological composition of waste separated by mechanical separation on a drum screen (Ø = 80 mm), i.e. the undersize and oversize fraction transferred to RDF (refuse derived fuel) production, and then to thermal processing in cement plants.

Table 3. Morphological composition of MSW, undersize and oversize fraction

Waste group	Share ± SD*	
	MSW	Undersize Ø < 80mm
	[g·kg^{-1} w.w]	[g·kg^{-1} w.w]
Fine fraction[a]	61.3 ± 31	129.4 ± 27
Organics[a]	289.4 ± 89	408.7 ± 79
Wood[a]	20.8 ± 4	11.8 ± 7
Paper and cardboard[a]	155.2 ± 45	99.8 ± 27
Plastics	226.4 ± 87	74.1 ± 23
Glass	64.4 ± 47	79.6 ± 34
Textiles[a]	47.8 ±22	27.7 ± 20
Metals	19.3 ± 12	11.2 ± 5
Hazardous waste	7.6 ± 3	11.4 ± 6
Multimaterial waste[a]	28.9 ± 13	37.6 ± 9
Personal hygiene products	32.2 ± 4	67.8 ± 8
Inert	25.3 ± 9	21.5 ± 13
Other categories	21.4 ± 11	19.4 ± 9
Total	1000	1000

[a] – biodegradable waste, * SD – standard deviation

The municipal waste is dominated by organics, plastics, paper and cardboard. The oversize fraction consists mainly of plastics, paper, cardboard and textiles. The share of biodegradable waste in the MSW stream was 50.9%, 22.95% in the oversize fraction and 58.2% in the undersize fraction, which stems from the large amount of organic waste and fine fraction. The share of biodegradable waste in the MSW stream is characteristic for waste from urban areas. For all mechanical processing of the waste treated in the second step (Fig. 1) an average of 57.13 ± 4.9% of the undersize fraction and 37.55 ± 4.6% fraction of the oversize fraction were separated. Moisture of the oversize fraction was in the range of 175–235 g·kg-^{1}, ash contents: 9.8 ± 1.4% d.m., combustion heat: 26.4 ± 1.6 MJ·kg^{-1} and caloric value of 19–21.5 MJ·kg^{-1}. The resulting shares were similar to those found by Malinowski (2012, 2013), who writes that even though the stream of mixed municipal waste is vastly heterogeneous (in terms of fractional and morphological composition), approximately 500 g of alternative fuel can be produced from 1000 g of mixed municipal waste in urban areas with high concentration of social and economic infrastructure. Waste from urban areas with single-family housing may yield approximately 380 g of alternative fuel from 1000 g of mixed waste, while waste from typical rural areas may yield as little as 270 g.

Figure 5 shows the typical variations in temperature (cross marks, °C) while dash marks shows the flow of inlet air (m^{3}·Mg^{-1}·h^{-1}) in the process of aerobic biological waste treatment (biostabilisation), according to Tambore et al. (2011). Temperature trend (dot marks – the average from 5 bioreactors) in the process of waste biostabilisation during the study is slower in the first 3 days, but higher maximum temperature of 65°C is reached due to self-heating. This temperature was maintained for several hours to inactivate pathogenic microorganisms (Jędrczak, 2008). High process temperature (> 50°C) was maintained for a long time due to the large mass of biological waste being processed. The air supply was maintained at 25–30 m^{3}·Mg^{-1}·h^{-1}. After 14 days the process of biodrying had been started and the air flow was increased to 80 m^{3}·Mg^{-1}·h^{-1} resulting in a rapid decline in temperature (from 48 to 19°C). The difference between readings from 3 sensors in each bioreactor did not exceed 3°C, and the differences in these readings were not statistically significant ($p<0.05$).

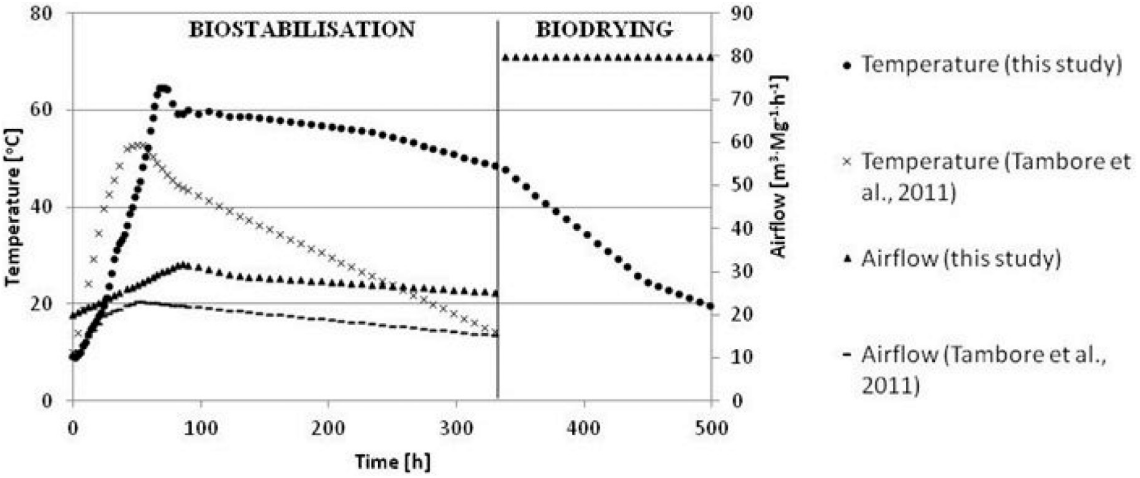

Fig. 5. Temperature and airflow-rate trends during biostabilisation and biodrying process in this study and in comparison with study of Tambore et al. (2011)

The average weight of waste undergoing biodegradation in each of the bioreactors was 15.6 ± 0.4 Mg. Thus, an average of 57.14% of the whole stream of municipal waste processed in the first step of mechanical treatment was transferred to the biological process. The average moisture content of the waste amounted to 468 g·kg^{-1} wet mass. After 14 days, moisture content decreased by 176.8 g·kg^{-1} wet mass, and after biodrying (further 7 days of intensive drying) the moisture content of the waste was on average 201 g·kg^{-1} wet mass (Table 4).

Table 4. Changes in weight and water content in the biological treatment of waste

Parameter	Unit	Bioreactor no. 1	Bioreactor no. 2	Bioreactor no. 3	Bioreactor no. 4	Bioreactor no. 5	Average ± SD
Mass – initial	[Mg]	15.6	15.5	16.2	15.4	15.3	15.6 ± 0.4
Weight after biostabilisation	[Mg]	11.3	11.7	11.5	11.3	11.8	11.5 ± 0.3
Weight after biodrying	[Mg]	10.3	10	11.1	10.6	10.3	10.5 ± 0.4
Moisture content – initial	[g·kg^{-1} w.w]	444	468	464	486	479	468.2 ± 16
Moisture content after 5 days of biostabilisation	[g·kg^{-1} w.w]	341	371	343	385	379	363.8 ± 20
Moisture content after 10 days of biostabilisation	[g·kg^{-1} w.w]	332	334	321	301	336	324.8 ± 15
Moisture content after biostabilisation	[g·kg^{-1} w.w]	322	307	250	280	298	291.4 ± 28
Moisture content after biodrying	[g·kg^{-1} w.w]	200	199	213	207	186	201 ± 10
Density – initial	[kg·m^{-3}]	540.2	534.4	558.6	531.1	527.6	538.4 ± 12
Density after biostabilisation	[kg·m^{-3}]	455.6	464.3	456.3	448.4	460.9	457,1 ± 6
Density after biodrying	[kg·m^{-3}]	446.8	432.9	479.3	452.8	436.6	449.7 ± 18

In the process of biodrying, more than 15% of the initial mass of the MSW was emitted from the reactor as CO_2 and H_2O. As a result of biological drying, further 4% of the initial MSW mass was transferred to the biofilter and then to the atmosphere. During biological treatment, more than 30% of mass which went into the bioreactor was transferred to the biofilter in the form of CO_2 and H_2O. The results are consistent with literature reports (Domińczyk et al., 2012; Adani et al., 2004).

The metal content in the waste depends on the presence of undesirable materials, such as ferrous and non-ferrous metals and hazardous waste such as batteries and fluorescent lamps. Waste segregation at source allows to reduce the contents of heavy metals in waste meant for biological processing (Latosińska, 2013). A significant increase in the contents of heavy metals was noticed after the stabilisation and biodrying (Table 5).

Table 5. The elemental composition of the analysed substances before and after biological treatment

Parameter	Unit	Undersize fraction	Waste after biostabilisation	Polish standards for organic fertilizers*
Element				
Na	$[g \cdot kg^{-1}]$	5.87	4.86	-
Mg		3.22	4.40	-
K		5.76	3.46	-
Ca		40.61	41.35	-
P		0.62	0.02	-
Cr		0.16	0.38	≤0.1
Mn		3.26	5.12	-
Fe		19.95	27.34	-
Ni	$[mg \cdot kg^{-1}]$	24.47	54.49	≤40
Cu		551.52	601.70	-
Zn		413.82	828.05	-
Cd		1.89	1.02	≤5
Pb		61.70	151.39	≤140
Hg		0.1047	0.3125	≤2
N	[% d.m.]	1.0148	0.6402	>0.3

* in accordance with the Regulation of the Minister of Agriculture and Rural Development dated 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization

The largest, nearly three-fold increase was observed in the case of lead and mercury. Two-fold increase was observed for nickel and zinc. The smallest average increase was observed for iron and manganese. The concentration of lead and nickel in the waste after biostabilisation exceeded acceptable levels set by the Polish standards for substances released into the soil as fertilizer (Regulation, 2008).

Loss on ignition LOI of undersize fractions were 77.1 ± 1.3% d.m. After stabilisation, LOI was much lower and amounted to 51.2 ± 2.5% d.m., which means that the stabilisation process is rapid. However, the resulting waste cannot be categorised as stabilised waste, since according to the requirements of MBS technology, the LOI should be lower than 35% d.m. or the loss of organic mass in the stabilisate as compared to the organic mass in the waste measured as a loss on ignition or carbon contents should be higher than 40% (Regulation, 2012). To achieve this value, the process should be continued for at least 2 weeks more. The process of stabilisation slows down due to the decreasing microbiological activity in the waste in the reactor, which is in turn caused by the lowering water content. In classic technologies, the values required by the Polish norms are achieved after 6 – 8 weeks of maturing in heaps, following the initial 14-day biostabilisation in reactors. Biological drying is a process that can accelerate further processing. This process is applicable at the time when the material being dried undergoes self-heating. When biostabilisation was interrupted, the temperature in the bioreactor was 48 ± 2.3°C.

Both the undersize fraction and the stabilisate had a relatively low calorific value (5.9 $MJ \cdot kg^{-1}$ and 8.6 $MJ \cdot kg^{-1}$, respectively), with high ash content, which was 22.9% d.m. in undersize fraction and 48.3% for the stabilisate (Table 6). It should be noted that ash is the so-called ballast for the fuel and directly influences its calorific value. In both cases, the volatile content fluctuates around 30 – 35% d.m. (Table 6). The amount of volatiles is important for the assessment of energetic suitability of fuel. Fuels with high volatiles levels burn with a longer flame and require additional air for smokeless burning. Despite this, the achieved calorific value for biodried waste guarantees auto-thermal incineration.

Table 6. Analysis of selected characteristics of waste

Parameter	Unit	Undersize fraction	Waste after biostabilisation	Waste after biodrying
pH	–	7.38 ± 0.3	7.56 ± 0.3	7.66 ± 0.3
Heat of combustion	[$kJ \cdot kg^{-1}$]	14253 ± 231	12004±303	11890±380
Calorific value	[$kJ \cdot kg^{-1}$]	5971 ± 151	8659±283	8574±298
Loss on ignition	[% d.m.]	77.1 ± 1.3	51.2±2.5	48.3±1.5
Ashes	[% d.m.]	20.9 ± 1.6	30.5±0.8	34.7±2.8
Volatiles	[% d.m.]	33.3 ± 1.5	–	35.8±1.5
Flammables	[% d.m.]	66.6 ± 4	–	54.8 ± 5

Biodried waste was ultimately divided into two fractions using a drum screen with hole diameter of 20 mm. The undersize fraction with size of 20 mm mostly consisted of mineralised waste that should be returned to the process or transported to the landfill after they have achieved the correct parameters. After the process, this fraction was directed to a landfill. Undersize fraction accounted for 37.6% of the waste after biodrying. The remaining fraction with grain size of 20–80 mm has the heat of combustion equal to 12.9 $MJ \cdot kg^{-1}$ and the calorific value of 9.8 $MJ \cdot kg^{-1}$.

Remaining mass after biodrying process has been tested of biogas production. In the two first days of the process, phase of hydration has occurred, therefore, the gas yield was minimal (Fig. 6). After hydration phase intensive increase of methane bacteria occurred as evidenced by the curve of the total amount of biogas yield.

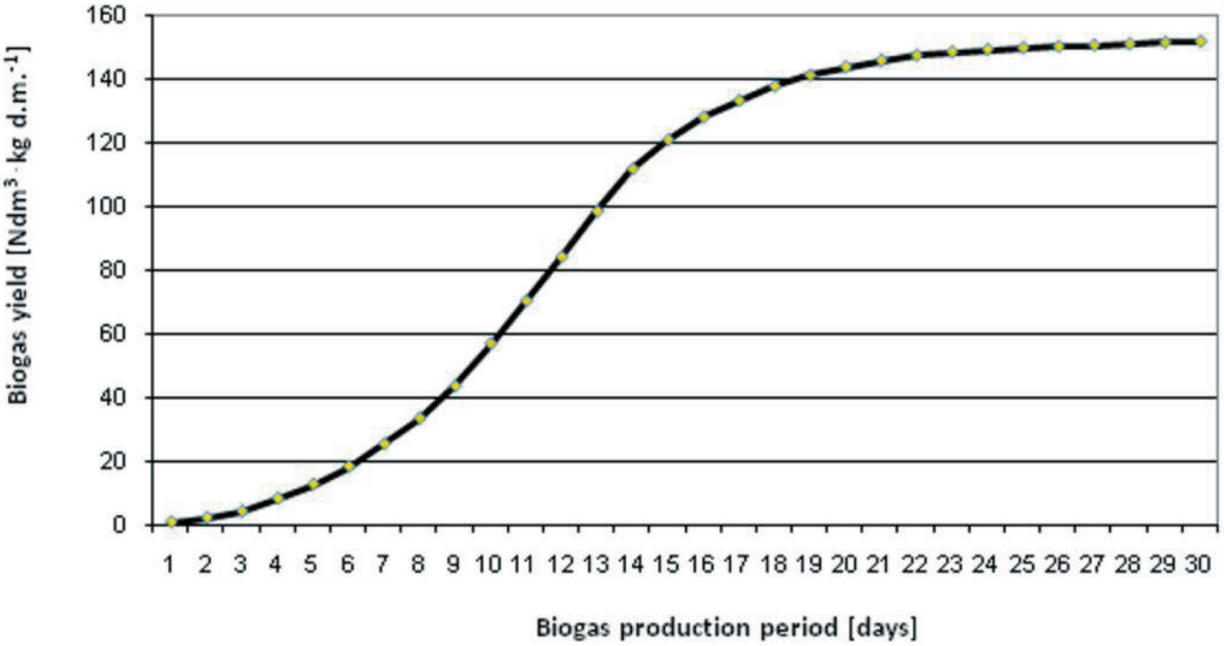

Fig. 6. The total amount of biogas yield

Inhibition of the process was not been observed. Till the sixth day of fermentation a delay of increase in volume of biogas was observed. After the retention time (30 days) total biogas yield was 140 $Ndm^3 \cdot kg$ d.m.$^{-1}$.

In the twentieth day of fermentation the highest methane content (Fig. 7) was recorded, reached the level of 46% CH_4 (38% CO_2 i 0.4% O_2). The content of methane started to decrease after the twenty-eighth days. Hydrogen sulphide content during the study was in the range from 149 to 320 ppm.

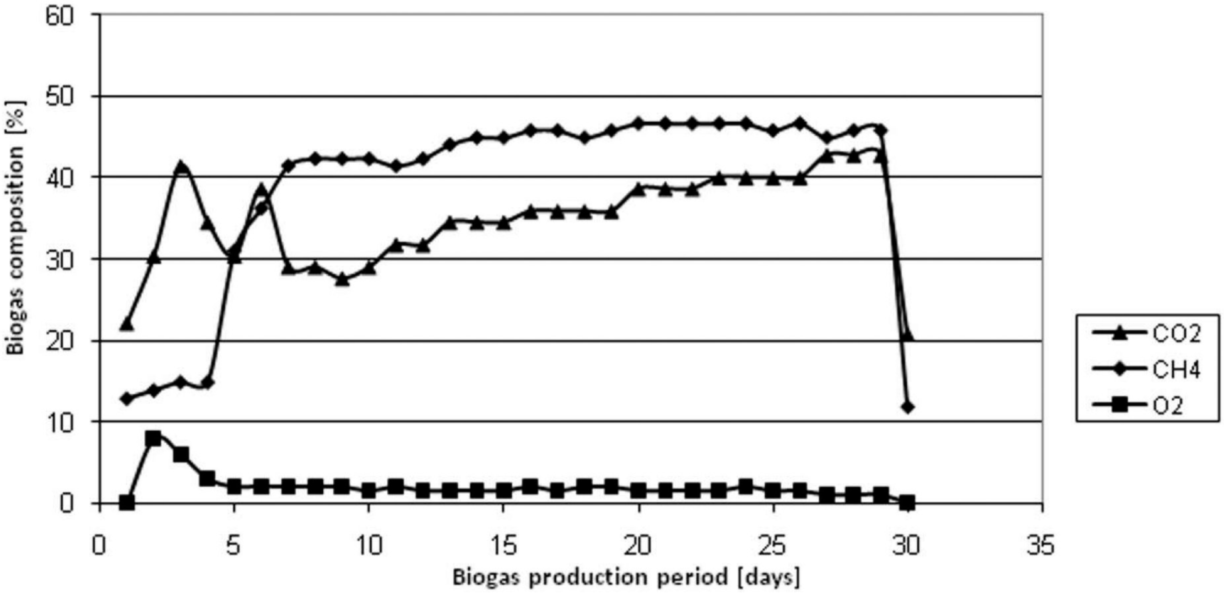

Fig. 7. Biogas composition

4. CONCLUSIONS

Mechanical – biological waste treatment as described in this article directly reduces the mass of waste deposited in the environment, especially at landfills. On the basis of the gained results the following conclusions were formulated:

- The biostabilisation and biodrying process using innovative technology described in article, allow to reduce the mass of waste going to landfilling. The MBT mass balance of waste shows that only 14.5% of the initial mass should be landfilled.
- During biological treatment, more than 30% of mass which went into the bioreactor was transferred to the biofilter in the form of CO_2 and H_2O, representing nearly 19% of the initial MSW.
- The evaluation of the results showed that the stabilised waste can be successfully used for energy purposes. 61.5% of the initial mass may be used to recover energy.
- Waste after biostabilisation are not useful for fertilization, because of exceeding concentration of lead and nickel.
- The technology described in this article does not ensure the generation of stabilised waste after 14 days of processing in a bioreactor alone. This arrangement also allows the plant to save space, which would be used for maturing stabilised waste. This method of stabilisation and biodrying waste should be further improved.

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REFERENCES

Abeliotis K., Kalogeropoulos A., Lasaridi K., 2012. Life Cycle Assessment of the MBT plant in Ano Liossia, Athens, Greece. *Waste Manage*., 32, 213–219. DOI: 10.1016/j.wasman.2011.09.002.

Adani F., Baido D., Calcatera E., Genevini P., 2002. The influence of biomass temperature on biostabilization-biodrying of municipal solid waste. *Bioresource Technol*., 83/3, 173 -179. DOI: 10.1016/S0960-8524(01)00231-0.

Adani F., Tambone F., Gotti A., 2004. Biostabilization of municipal solid waste. *Waste Manage*. 24, 775–783. DOI: 10.1016/j.wasman.2004.03.007

Binner E., 2003. Mechanical–biological pre-treatment of residual waste in Austria. In: Dhir R.K., et al. (Eds.), In: *Proceedings of the International Symposium, Sustainable Waste Management*. University of Dundee, Scotland, UK 9–11, September 2003. 213–224.

Council Directive 99/31/EC of 26 April 1999 on the landfill of waste. *Official Journal of the European Communities*, 16.7.1999, L182/1 – L182/19.

Dębicka M., Żygadło M., Latosińska J., 2013. Investigations of bio-drying process of municipal solid waste. *Ecol. Chem. Eng. A*., 20, 1461–1470 DOI: 10.2428/ecea.2013.20(12)132.

Dias N., Belo N., Máximo A., Carvalho M.T., 2014. Recovery of glass contained in the heavy residual fraction of Portuguese mechanical Biological Treatment Plants. *J. Cleaner Prod.*, 79, 271–275. DOI: 10.1016/j.jclepro.2014.05.028.

DIN 38 414, 1985. *Determination of digestion behaviour ”sludge and sediments”*. Beuth Verlag, Berlin (in German).

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*, L312/3 – L312/30.

Domińczyk A., Krzystek L., Ledakowicz S., 2012. Bio-drying of mixture of solid waste from the paper industry and the organic fraction of municipal solid waste. *Inż. Ap. Chem.* 51, 115–116 (in Polish).

European Committee for Standardization, 2006. *Characterization of waste – Sampling of waste materials – Framework for the preparation and application of a sampling plan*. EN 2006, 14899.

Flamme S., 2006. The biogenic content in substitute fuels. *Aufbereitungs-Tech./Mineral Process*, 47, 40–45.

Garg A., Smith R., Hill D., Longhurst P.J., Pollard S.J.T., Simms J., 2009. An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. *Waste Manage*. 29, 2289–2297. DOI: 10.1016/j.wasman.2009.03.031.

Ibbetson C., 2006. UK market development of solid recovered fuel from MBT plants. In: *Waste 2006 – Sustainable Waste and Resource Management*, Stratfordupon-Avon, UK, 19–21 September 2006, Paper 2B-15.00.

Jędrczak A., Szpadt R. 2006. Określenie metodyki badań składu sitowego, morfologicznego i chemicznego odpadów komunalnych. NFOŚiGW. Kamieniec Wrocławski, Zielona Góra (in Polish).

Jędrczak A. 2008. *Biological treatment of waste*. PWN, Warszawa (in Polish).

Kuehle-Weidemeier M., 2007. The current situation of MBT in Germany. In: Kuehle-Weidemeir M. (Ed.), *International Symposium MBT 2007*. Hanover, Germany, 22–24 May 2007, 187–202.

Latosińska J., 2013. *Utrzymywanie czystości w gminie*. Wyd. Politechniki Świętokrzyskiej, 1, 47–48 (in Polish).

Malinowski M., 2012. The restrictions of mixed municipal waste treatment to alternative fuels. *Episteme*, 14/2012, 101–108 (in Polish).

Malinowski M., 2013. Selected properties of alternative fuel manufactured from municipal solid waste. *Infrastructure and ecology of rural areas*. 2013/04, 125 – 139.

Mohn J., Szidat S., Fellner J., Rechberger H., Quartier R., Buchmann B., Emmenegger L., 2008. Determination of biogenic and fossil CO_2 emitted by waste incineration based on $^{14}CO_2$ and mass balances. *Bioresour. Technol*. 99, 6471–6479. DOI: 10.1016/j.biortech.2007.11.042.

Patent Application no 121933 in Polish Patent Office.

Pires A., Martinho M.G., Silveira A., 2007. Could MBT plants be the solution of fulfil landfill directive targets in Portugal? In: Kuehle-Weidemeir, M. (Ed.), *International Symposium MBT 2007*. Hanover, Germany, 22–24 May 2007, 63–72.

PN-EN 14774-3:2010, Solid biofuels – Determination of moisture content – Oven dry method – Part 3: Moisture in general analysis sample.

PN-EN 14775:2010, Solid biofuels – Determination of ash content.

PN-EN 15148:2010, Solid biofuels – Determination of the content of volatile matter.

PN-EN 15169:2007, Characterization of waste – Determination of loss on ignition in waste, sludge and sediments.

PN–ISO 1928, Solid fuels – Determination of combustion heat by combustion in a bomb calorimeter and calculation of net calorific value.

PN-Z 15008-04:1993, Municipal solid waste – Testing of fuel – Determination of the heat of combustion and calculation of net calorific value.

Regulation of the Minister of Agriculture and Rural Development of 18 June 2008 on the implementation of certain provisions of the Act on fertilizers and fertilization. *Dz.U. 2008* no 119, 765. Available at: http://isap.sejm.gov.pl/DetailsServlet?id=WDU20081190765

Regulation of the Minister of Environment of 11 September 2012 on the mechanical – biological treatment of mixed municipal waste. *Dz.U. 2012*, 1052. Available at: http://isap.sejm.gov.pl/DetailsServlet?id=WDU20120001052.

Regulation of the Minister of Economy of 8 January 2013 on the criteria and procedures for the acceptance of waste for landfilling of given waste type. *Dz.U. 2013*, 38. Available at: http://isap.sejm.gov.pl/DetailsServlet?id=WDU20130000038.

Sikora J., 2012. The research on efficiency of biogas production from organic fraction of municipal solid waste mixed with agricultural biomass**.** *Infrastructure and ecology of rural areas*. Nr 2012/02/4, 89 – 98 (in Polish)

Steiner M., 2005. MBT in Europe: roles and perspectives. *Warmer Bull.* 102, 14–17.

Steiner M., 2006. MBT in Europe: roles and perspectives (part 2). *Warmer Bull*. 103, 8–11.

Sugni M., Calcatera E., Adani F., 2005. Biostabilization-biodrying of municipal solid waste by inverting air-flow. *Bioresource Technol*., 96, 1331–1337. DOI: 10.1016/j.biortech.2004.11.016.

Tambore F., Scaglia B., Scotti S., Adani F., 2011. Effects of biodrying process on municipal solid waste properties. *Bioresource Technol.*, 102, 7443–7450. DOI: 10.1016/j.biortech.2011.05.010.

Titta G., Viviani G., Sabella D., 2007. Biostabilization and biodrying of municipal solid waste. *Eleventh International Waste Management and Landfill Symposium*. Cagliari, Sardinia, Italy, 1–5 October 2007, 1085–1086.

Velis C.A., Longhurst P.J., Drew G.H., Smith R., Pollard S.J.T. 2009. Biodrying for mechanical–biological treatment of wastes: A review of process science and engineering. *Bioresour. Technol*.100, 2747–2761. DOI:10.1016/j.biortech.2008.12.026.

Yasuhura A., Amano Y., Shibamoto T., 2010. Investigation of the self-heating and spontaneous ignition of refuse-derived fuel (RDF) during storage. *Waste Manage*. 30, 1161–1164. DOI: 10.1016/j.wasman.2009.11.003.

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