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The Effect of Selected Parameters on the Stabilization Efficiency of the Organic Fraction of Municipal Solid Waste (OFMSW) in the Mechanical and Biological Treatment Plant (MBT)

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1. Introduction

Composting is a waste recycling method based on the biological degradation of organic matter under aerobic conditions, by many populations of microorganisms producing stabilized, deodorized and disinfected compost (Fourti 2013; Wei et al. 2017), which reduces the amount of waste neutralized and/or released into the environment (Skaggs et al. 2017).

Composting is an aerobic process, which requires oxygen for microbial biodegradation, optimal moisture, and porosity (Gea et al. 2007). In the course of a composting process, the most common procedure for aeration is through turning of the compost material. These facts make composting material readily available for microbial utilization and thus, results in gas emission (Onwosi et al. 2017). Composting requires relatively low technological advancement and a low investment cost (Gea et al. 2007), compared to other treatment technologies, i.e. anaerobic digestion. As a waste treatment method, composting can divert waste from landfill, mitigate groundwater contamination, reduce air pollution and greenhouse gas emission (Li et al. 2013; Oliveira et al. 2017). It can be applied to mixed municipal solid waste (MSW) as well as separately collected biodegradable fraction (Diaz, 2002). In the case of mixed MSW, a combination of mechanical, other physical and biological processes are required (Baptista et al. 2010). There has been increasing attention on improving the management of the organic fraction of municipal solid waste (OFMSW). Biodegradable material, especially food waste, usually accounts for over 50 wt% of the municipal/residential waste stream in less developed countries (Wei et al. 2017). In full-scale composting process is realized in the so-called mechanical – biological treatment (MBT) plant. In the case of MBT, the main aim of composting is to maximize stabilization of the organic fraction of municipal solid waste (OFMSW) before its final disposal (Colón et al. 2017).

Composting is a natural process; however, many artificial factors have been developed to improve process efficiency (Xi et al. 2005). The decomposition of the organic matter is affected by several factors that can be divided into two general groups: variables which determine the concentrations of the biodegradable compounds, affect microbial population size and its activity; and factors that directly control the reaction kinetics itself, such as: temperature, oxygen ratio, moisture content (Hamoda et al. 1998; Onwosi et al. 2017).

Temperature, oxygen and moisture content are often selected as the control variables in the composting process, jointly with another chemical, biochemical or microbiological properties (Gea et al. 2007). Regardless of whether stabilized organic residues are recovered or stored, the assessment of the effectiveness of the biological process is critical (Cesaro et al. 2016).

The resistance of the organic matter against extensive degradation or toward significant microbiological activity means compost stability. Maturity describes the ability of a product to be used effectively in agriculture and is related to the growth of plants and phytotoxicity aspects (Oviedo-Ocana et al. 2015; Cerda et al. 2017).

Since OFMSW is heterogeneous material and usually cannot be modified, management of the composting process has to be focused on environmental factors. Furthermore, OFMSW composition has been observed as an individual for different countries or even for each MBT plant. Although much research on the composting process conditions exists (Barrena Gómez et al. 2006; Waszkielis et al. 2013), only a few focused on stabilization in full scale (Gutiérrez et al., 2017; Gutiérrez et al. 2015; Sadef et al., 2015). Moreover, the available literature contains no references to similar raw-materials as used in the present research.

There are many tests of compost stability and maturity; however, there is still no universally accepted method for measuring compost stability or maturity index (Komilis et al. 2011). Stability of compost is assessed based on respirometry (a measurement of the produced carbon dioxide or oxygen consumed by microorganisms), which allows estimating the potential biological activity (Fourti 2013; Cerda et al. 2017). A high maturity index is necessary when the compost is to be used as a nutrient for soil and fertilizer (Huang et al. 2017).

In the composting process, respiratory activity has become an essential parameter in determining the stability of compost, as well as for monitoring the composting process and is considered an important factor for assessing the maturity of the material (Barrena Gómez et al., 2006). Higher rates of carbon dioxide release or oxygen consumption characterize less stable composts. Compost can be referred to as very mature, mature, and immature (Fourti 2013). A drawback of respirometric tests is the use of different temperatures and the amount of sample. It is assumed that respirometric measurements should be performed at 35-37°C.

The most recognizable respirometric indicators are effective breathing rate (DRI) and cumulative O2 consumption after four days (AT4) (Barrena Gómez et al. 2006). These indicators have been used successfully as indicators of stability in tests both on a laboratory scale and on an industrial scale (Barrena Gómez et al. 2006; Cerda et al. 2017; Colón et al. 2017). In case when the aim of composting is to produce so-called stabilized bio-waste, depending on the standards in the European Union, the AT4 value in the final product should amount from 5 (Germany), by 7 (Austria) to 10 (Poland) mg O_2 / g dry matter. If the whole process is carried out in two stages with the use of closed reactors or composted windrows aerated in halls, by the relevant regulations, the end of the first so-called hot phase requires material stabilization at the level AT4 =20 O_2/g dry matter (Sidełko et al. 2017).

The self-heating test measures the temperature rise due to the heat released from the biological and chemical activity of the compost sample. It is a simple method, and the results are easy to understand. This test cannot be directly correlated with breathing, because many chemical and biochemical reactions unrelated to breathing are also exothermic. Furthermore, other factors such as porosity or humidity also affect the heating of biomass (Barrena Gómez et al. 2006).

This study aimed to assess the effect of aeration, irrigation, turning frequency and process time on OFMSW stabilization after the intensive degradation phase of compositing in a full-scale MBT plant.

2. Materials and methods

2.1. Composting material

The material used in this study was obtained from Waste Management Company, located in Lower Silesia Region, Poland, a Mechanical Biological Treatment (MBT) plant. The mechanically pretreated wastes consist of sieving to 60 mm diameter and the magnetic separation of ferrous materials. The organic fraction of municipal solid waste (OFMSW) is characterized in Table 1.

Table 1. Characterization of the OFMSW fraction

Fraction	Content [%]	Fraction	Content [%]
Fruits	7.2	Inert waste	5.9
Vegetables	5.1	Textiles	0.6
Other biowastes	12.3	Metals	0.87
Wood	0.4	Dangerous materials	0.3
Paper	6.1	Tetrapack	4.2
Plastics	3.5	Others	7.3
Glass	10.3	0-15 mm fraction	35.93

2.2. Composting facility

The six enclosed box reactors (pile size 21.5 m x 7.5m x 2.0 m) with irrigation and positive aeration by a blower with air capacity 60.5 m^3/min were used during experiments. The scheme of the process is presented in Figure 1.

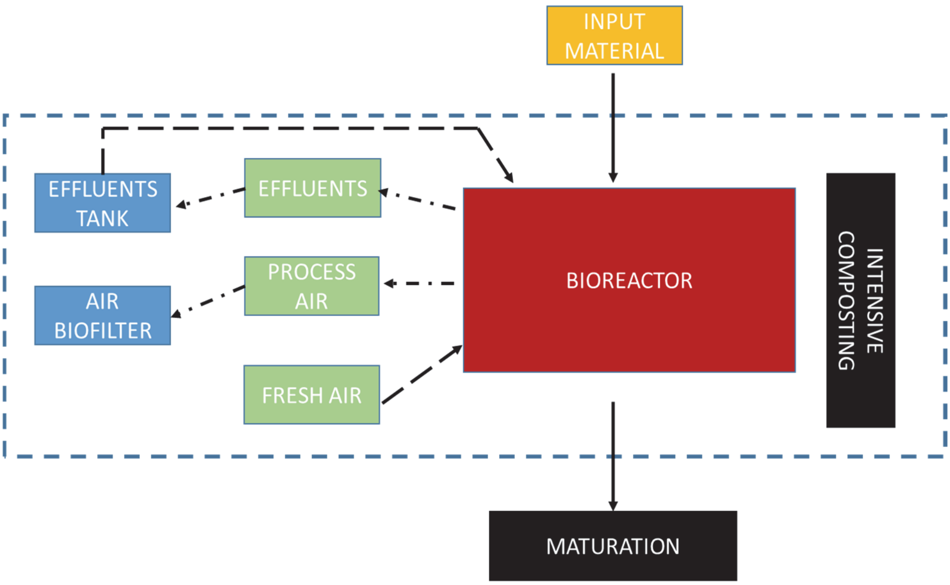

Fig. 1. The scheme of composting process facility

The temperature was measured using stainless temperature probes 2 m long. The probe had three sensors located at distances 20 cm apart, starting from the tip of the probe.

2.3. Sampling method

Ten to twelve sub-samples were taken from a pile to obtain representative samples, directly in the composting facility, and mixed in a clean pail. The weight of the sample after mixing sub-samples was approximately 10-15 kg. All analyses were done using neither frozen nor conditioned material.

2.4. Analytical methods

Stabilization of the material was determined using the self-heating test. Dewar flasks (2.0 dm^3 capacity; 100 mm internal diameter) equipped with electronic memory thermometers were used as the Dewar Kit (Brinton et al. 1995). Determination of moisture was done using a squeeze test (Anonymous 2009). If the compost was found to be too dry, water was added. If the compost was too wet, it had to be dried overnight by spreading on a flat, clean surface. After confirmation of the optimal moisture for the test, the Dewar flask was filled with compost chilled to room temperature and the thermometer probe was inserted. The internal temperature was measured at 2h intervals throughout the experiment. The moisture content was determined gravimetrically with oven drying at 105°C.

2.5. Statistical analysis

To assess how the irrigation, aeration, turning frequency and process time influence the OFMSW stabilization. The fractional factorial plan ($2^{(4-1)}$) for four factors on two levels with two replicates was generated using Design of Experiments Module of STATISTICA version 10 (StatSoft, Inc., 2011, USA) (Table 2).

Table 2. The experimental design matrix with coded values

Run	X1 aeration of the pile	X2 irrigation	X3 time of the experiment	X4 turning of compost
1	-1	-1	-1	-1
2	-1	-1	1	1
3	-1	1	-1	1
4	-1	1	1	-1
5	1	-1	-1	1
6	1	-1	1	-1
7	1	1	-1	-1
8	1	1	1	1

The fitted first-order model is:

$$Y=\beta_0+\sum\beta_i X_i, \quad (1)$$

where:
Y – the predicted response,
β_0 and β_i – constant coefficients,
X_i – the coded independent factors.

The aeration (X_1) was determined by blower working time. For minimum value after 5 minutes blowing, 10 minutes break appear. For the maximum value, the working time and pause period were changed respectively. The irrigation level (X_2) was set up for 5000 dm^3/ d as a minimum and 10000 dm^3/d as a maximum. The process was planned for 2 or 4 weeks (X_3) and in that time weekly frequency turning (X_4) was done or not.

The effect on stabilization efficiency of each variable was determined by equation (2):

$$E_{(xi)} = (\sum M_{i+} - \sum M_{i-})/N, \quad (2)$$

where:
$E_{(xi)}$ – the main effect of the tested variable on stabilization efficiency,
M_{i+} and M_{i-} – the stabilization where the variable (xi) measured was at a high and low value, respectively,
N – the number of runs (Chauhan et al. 2007).

The standard error (SE) of the stabilization effect was the square root of the variance of an effect, and the significance level (*p-value*) of each stabilization effect was determined using Student's t-test (3):

$$t_{(xi)} = E_{(xi)}/ SE, \quad (3)$$

where:
$E_{(xi)}$ – the effect of variable *xi* (Chauhan et al. 2007).

The results of the experimental design were analyzed and interpreted using STATISTICA StatSoft ver. 10. All statistical tests were evaluated at the 95% confidence level.

3. Results and discussion

The OFMSW used by Gutierrez et al. (2015) was separated manually from the voluminous matter, and particles higher than 80 mm in diameter removed. It consisted of different percentages of organic matter, glass, plastic, paper-card, and others, being the organic matter the most abundant components

(63%) (Gutiérrez et al., 2015). The material used in this study was pretreated mechanically, and the size of particles was not bigger than 60 mm (Table 1).

Figure 2 shows the reduction of self-heating possibility of OFMSW after the intensive degradation part of the composting process.

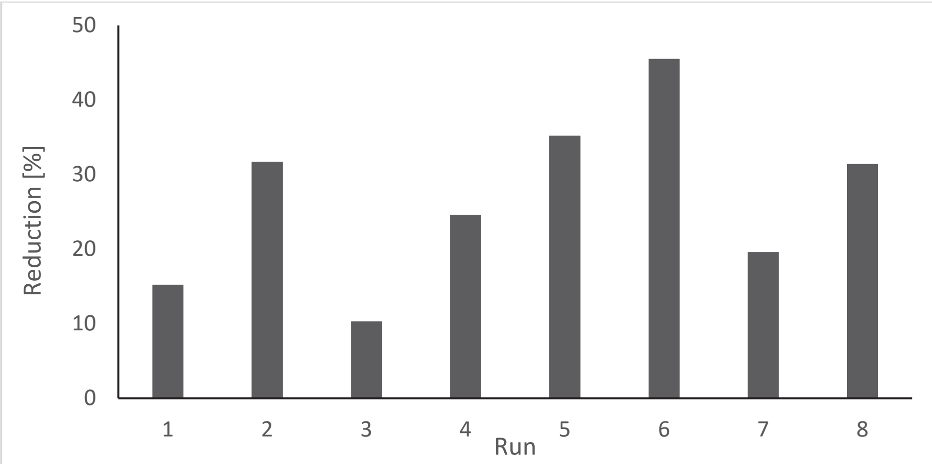

Fig. 2. Reduction in self- heating possibility after composting

The highest stabilization yield was noticed for four weeks processes. The lowest one was observed in run no 3, which characterized minimum aeration and composting time with maximal irrigation. Based on the Dewar test results statistical analysis was done, and the results are presented in Table 3.

Table 3. The statistical analysis of obtained results

Factor	Effect	t ratio	P value	Significance*
Aeration	0.0586	4.6715	0.0095	"+"
Irrigation	-0.0484	-3.8548	0.0182	"+"
Time	0.0624	4.9704	0.0076	"+"
Turning	0.0823	0.6128	0.5833	"-"

* Significant at $p \leq 0.05$, standard error = 0.0355, $R^2 = 0.94$

Among four factors, mechanical turning was found not to significantly influence the effect of stabilization. The determination coefficient (R^2) of 0.94 (which means that the model explains 94% of the total variation) suggests an adequate representation of the process model and a good correlation between the experimental and predicted values (Brinques et al. 2010; Seruga and Krzywonos 2015). Therefore, a linear equation which describes the response of material stabilization can be planned:

$$Y = 0.263 + 0.058X_1 - 0.048X_2 + 0.062X_3 \quad (4)$$

where:
Y – predicted response,
X_1, X_2, X_3 – coded values of the factors according to Table 2.

The positive coefficients for aeration and process time indicate a linear effect increment in stabilization, while the negative values for irrigation indicate a direct effect on the decrement. For this statement confirmation, a control run was conducted.

The achieved stabilization yield was about 47.5%, where the aeration (X1) was set up as blower working cycle: 10 minutes blowing and 5 minutes break, the irrigation level (X2) was set up for 10000 dm^3/d and process was performed 4 weeks (X3).

The turning frequency has been proved to be a factor that affects the decomposition as well as compost quality (Smith and Hughes 2004; Ogunwande et al. 2008; Getahun et al. 2012; Sidełko et al. 2017). Getahun et al. (2012) conducted experiments on a specially prepared mixture of biodegradable municipal solid waste and carried out in 3 bins with different turning frequencies. They have confirmed that the decomposition rate increased with increasing turning frequency – furthermore, the shortest maturation time they have noticed for the highest turning frequency. However, at full scale, the high frequency of turnover generates costs and requires proper management (Colón et al. 2017), thus its limitation can optimize exploitation costs. Based on this study results and statistical analysis impact on material stabilization of turning frequency was not confirmed. Probably due to short process time of intensive degradation: 2-4 weeks, other process conditions and material characteristic, mainly proper porosity to ensure air flow inside the pile without loosening of material occurring during turning.

Moisture content is a critical parameter in the composting process (Petric et al. 2012). This statement was also confirmed Iqbal et al. (2015) when study optimization of process parameters for the decomposition of kitchen waste into mature, stable compost used Box-Behnken design. Oviedo-Ocana et al. (2015) have noticed a steady drop in moisture during the composting process, which was the result of the increase in temperature and the rotation of the material. Despite the production of water in the biochemical process, the net loss of water occurs during open composting.

Composting in open systems causes the release of a significant amount of odors that disrupt the well-being of residents. However, the initial composition of the composted material affects the production of volatile organic compounds and the emission of odors during the composting process (Gutiérrez et al. 2017).

As expected, a longer composting time affects the temperature decrease in the windrow and better stabilization. Results of this study have been confirmed by Siemiątkowski (2014), who determined the decomposition of the OFMSW by measuring: respiration activity – AT4 parameter (based on CO_2 production over four days), loss-on-ignition and total organic carbon content. In similar process conditions (with aeration and irrigation) material stabilization was related to process time. After five weeks of the composting value of AT4 parameter decreased to 5.29 mg O_2/g of organic matter (Siemiątkowski 2014).

The air blowing into the pile has to provide enough oxygen to enable aerobic degradation of substrates. The enforced aeration rate impacts the oxygen concentration inside a pile, cooling of the material, pathogen destruction and finally decomposition (Li et al. 2013). This factor has been confirmed in our research as significant for composting with a positive impact on decomposition. Previous studies, provided on sewage sludge confirmed that statement. In each research, the increasing of the aeration rate influences on higher stabilization and better compost quality (Hamoda et al. 1998; Dach et al. 2007; Colón et al. 2017).

As the nutrients for the microorganisms must be dissolved in water before they can be assimilated, water content is essential for the composting process (Hamoda et al. 1998). The optimum value of moisture has been found as 60 %. The content of water higher than 60% will prevent oxygen diffusion through the pile, as the voids will be filled with water and the free air space will be eliminated. In the case of low moisture, there will be no water for the dissolving of the organic matter. In both cases, organic matter degradation will decrease.

There were slight increases in the pile temperatures immediately after each turning operation in the early days of the experiment. The turning operation was responsible for the rise and fall pattern of the temperature profile and has been reported as the re-activation of the composting process (Ogunwande et al. 2008).

In this study, an increase in irrigation harms material stabilization. It confirms that after reaching optimum moisture, additional water has an adverse effect. It was found that the rate of oxygen uptake increases linearly with the increase of moisture and it reaches its maximum value at about 50-70%, after which the rate begins to decrease. Furthermore, below 20% very little biological activity occurred (Richard et al. 2002). Siemiątkowski proved that low water content with no irrigation during the process resulted in "dry stabilization". It means that after re-irrigation, all biological processes will start again (Siemiątkowski, 2014).

Using the simple method for stability test and Design of Experiments methods were able to get quite fast results without testing all possible combination of variables. It is crucial when having in mind the costs of the process. The costs for MBT plants are tough to compare because they depend on the technology used (AD or composting), treatment capacity, amount of impurities which required mechanical pre-treatment), but the most important is the characteristics of composted material (Colón et al. 2017). According to Abdoli et al. (2019) net present value in the internal rate of return for producing compost using aerated static piles was equal to 12.4%. In most cases, MTB's operating costs are the result of an agreement between the public administration and private enterprises managing MBT plants. For this reason, the costs also have other variables than strictly technological aspects (Colón et al. 2017).

4. Conclusions

As for all biological processes, the reaction rate can be influenced by various factors. In the case of composting of OFMSW in full-scale in MBT plant, which is known as being difficult to study and control, simple methods should be investigated. Dewar tests might be used as a simple method for control composting process directly in full-scale MBT plant. Determined material stabilization can be used for composting optimization, considering factors that can be modified. It has been found that aeration, irrigation and process time influenced the composting process, while mechanical turning was revealed to be insignificant. It has also been found that an increase in irrigation harms material stabilization. The OFMSW composting in full-scale focused on material stabilization with the lowest cost. That is why the results of this study might be useful for MBT plants.

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Abstract

Composting is a natural process; however, many artificial factors have been developed to improve process efficiency for the organic fraction of municipal solid waste (OFMSW) stabilization in the mechanical – biological treatment (MBT) plant. The study aimed to assess the effect of aeration (X1), irrigation (X2), process time (X3) and turning frequency (X4)on OFMSW stabilization after the intensive degradation phase of compositing in a full-scale MBT plant. The four-factorial design on two levels with two replicates was used to the optimization of compost stabilization yield. Among analyzed factors, mechanical turning was found not to significantly influence the effect of stabilization. The achieved determination coefficient (R^2) of 0.94 suggests an adequate representation of the process model and a good correlation between the experimental and predicted values. The achieved stabilization yield obtained in the control run was 47.5%, where the aeration (X1) was set up as blower working cycle: 10 minutes blowing and 5 minutes break, the irrigation level (X2) was set up for 10000 dm^3/d and process was performed 4 weeks (X3).

Keywords:
municipal solid waste, composting, mechanical-biological treatment,
organic fraction, DOE

Wpływ wybranych czynników na efektywność procesu stabilizacji organicznej frakcji odpadów komunalnych (OFMSW) w zakładzie obróbki mechaniczno-biologicznej

Streszczenie

Kompostowanie to zachodzący naturalnie tlenowy proces biodegradacji wykorzystywany przemysłowo zwłaszcza do przetwarzania odpadów. Opracowano i określono wiele parametrów tego procesu w celu poprawy wydajności procesu stabilizacji frakcji organicznej odpadów komunalnych (OFMSW) w zakładzie obróbki mechaniczno-biologicznej (MBT). Niniejsza praca miała na celu ocenę wpływu napowietrzania (X1), nawadniania (X2), czasu trwania procesu (X3) i częstotliwości przewracania pryzmy (X4) na stabilizację OFMSW uzyskanej po intensywnej fazie kompostowania w zakładzie MBT. Do optymalizacji wydajności stabilizacji kompostu wykorzystano czteroczynnikowy plan eksperymentu (DOE) na dwóch poziomach z dwoma powtórzeniami. Stwierdzono, że mechaniczne przewracanie pryzmy nie ma statystycznie istotnego wpływu na efektywność stabilizacji. Osiągnięty współczynnik determinacji (R^2) wynoszący 0,94 sugeruje odpowiednią reprezentację modelu procesu i dobrą korelację między wartościami eksperymentalnymi i przewidywanymi. Uzyskana wydajność stabilizacji uzyskana w przebiegu kontrolnym wyniosła 47,5%, przy ustawieniu czasów pracy wentylatora napowietrzania jako 10 minut działania i 5 minut przerwy (X1), nawadniania na poziomie 10 000 l/dobę (X2) i eksperymencie trwający, 4 tygodnie (X3).

Słowa kluczowe:
odpady komunalne, kompostowanie, mechaniczno-biologiczne przetwarzanie, frakcja organiczna, metoda planowania eksperymentu