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Optimizing municipal biodegradable waste management system to increase biogas output and nutrient recovery: a case study in Lithuania

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Abstract

Despite large investments to modern centralised mixed municipal waste (MMW) management plants (mechanical biological treatment (MBT)), environmental impact has been decreased less than was expected due to several determined reasons in Lithuania. Energy consumption for MMW management exceeds production volume of alternative energy in municipal biodegradable waste (BDW) fermentation equipment. Produced "technical compost" does not correspond to the requirements for contamination and quality of compost to be used in agriculture and can be used only as a stabilate for overlay of landfill layer and landfill restoration. This article presents the results of optimization possibilities of municipal BDW management in one of the Lithuanian regions. A few alternatives were suggested, but the source separation of municipal BDW from individual household was selected for implementation as the best available alternative for the target region from a technical, environmental, and economic point of view. The results of the carried out experiment with the source separation of municipal BDW and processing in the tunnel of the existing MBT plant have shown that biogas output can increase up to 114 m^3 per tonne of the municipal BDW. This approach would allow increasing alternative energy production in MBT plant by 4.9 times and producing compost instead of the stabilate. In case of the target region, overall alternative energy production would exceed energy demand (including for BDW transportation), by over 7 thousand GJ per year. Thus GHGs (without biogenic CO_2) would decrease by approximately 600 tonnes per year.

Keywords: municipal biodegradable waste management; nutrient recovery; anaerobic fermentation; biogas output

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1. Introduction

Municipal solid waste (MSW) accounts only for 7–10 % of the total waste generated in the European Union, however, it is predicted that global municipal solid waste generation may double by 2025 [1] Despite relatively small amount of MSW in an overall context, the stream requires significant efforts for management. These efforts are basically associated with MSW composition, complexity, and consumption patterns [2]. Regarding composition, food waste consists a large amount of MSW, for instance, Europe's average is 37.5 %, but the percentage varies significantly [2, 3]. Unlike any other biodegradable waste stream, food waste is characterised by outstanding heterogeneity leading to well biochemically balanced material for anaerobic treatment [4]. The major causes are relatively high concentrations of carbohydrates, proteins, fats and absence heavy metals [4]. These characteristics are a part of the reason why food waste has the highest biogas potential compare to other biodegradable waste (BDW) streams [5].

Biogas volume generated from municipal food waste in laboratory scale anaerobic conditions has shown promising potential. In 2008, the report published in Green Paper by European Commission revealed that 100–200 m^3 of biogas per tonne of food waste can be generated during anaerobic treatment. However, biogas output depends on BDW and fermentation technology used. Since then, a considerable number of studies has been conducted showing even larger recovery of biogas, for instance, 220 m^3 per tonne of food waste [6]. Moreover, researchers have scrutinised anaerobic digestion, in terms of, co-digestion, possible pre-treatment methods, and micronutrients presence allowing to enhance the treatment, in some cases, to generate up 30 % more biogas [5–8]. Nevertheless, when food waste reaches centralised a biological treatment plant through a MSW stream, the biogas output significantly reduces, for example, Pavi at al. [9] reported that cumulative biogas yield was 41.87 m^3 per tonne of municipal BDW, while theoretical biogas output is approximately 130 m^3 per tonne of BDW [10]. Some researchers relate this reduction to the presence of propionate acid, low pH, high concentration of NH^{4+} and heavy metals [11]. Concerning heavy metals, Abdel-Shafy at al. [12] reported that by adding 0.5 mg/kg of mercury, biogas output decreases dramatically, up to 92 %. Similar tendencies were observed by supplementing cadmium and chromium. The addition of cadmium (0.68 mg/kg) reduced biogas output by 84.8 %, while chromium (3.10 mg/kg) by 83 % [12]. Heavy metals, in particular, cause not only biogas output reduction, but also contamination of final compost [13].

Compost, produced in centralised MBT equipment, is characterised by a large amount of pollutants and low overall quality. The study conducted by Montejo et al. [14] have shown that 29 from 30 samples of MSW compost taken exceeded threshold limits of heavy metals presented in the legal requirements; a percentage of impurities were excessively high in most of the samples. Other researches confirm that the concentration of heavy metals, organic and inorganic impurities, sulphates and chlorides is exceeding threshold limits, moreover, they state that a content of organic matter, total phosphorus and total nitrogen are relatively low (main quality parameters of compost) [15]. Due to poor quality, this compost is no longer applicable in agriculture and can only be used as a stabilate for overlay of landfill layer and landfill restoration leading to immobilised circulation of bio-nutrients like nitrogen and phosphorus [16–18]. To cope with this problem, Yunmei et al. [15] suggest source separation as the best and most promising strategy for heavy metals control. The approach is confirmed by Kupper et al. [19] who found that heavy metals concentrations in MSW composts and solid digestates from source separated material met legal requirements despite used treatment technology.

In Lithuania, anaerobic BDW digestion is a widely applied management method due to generation of renewable energy, reduction of landfilling, stabilization of biodegradable material, and mitigation of climate change [20–22]. This method was chosen for centralised biological treatment of BDW from municipal waste stream in 4 out of 11 regions [16, 17]. The total capacity of these plants is over 77 thousand tonnes of municipal BDW per year (15 % of total municipal BDW, generated in Lithuania). Two different technologies of batch reactors are dominating: dry fermentation and fully dry fermentation technology, provided by Bekon [23]. The plants started operating in 2016–2017, and it was planned to recover more than 100 m^3 of biogas per tonne of BDW, to offset plants' energy needs and to produce excess energy. However, a monitoring of implemented MBT equipment with dry fermentation of separated BDW fraction showed that energy produced is not sufficient to cover electricity and heat energy demand for centralised equipment.

Many articles have been published regarding anaerobic reactor optimization in terms of biogas output. However, there is a limited number of articles addressing optimization of municipal food waste management system to increase biogas output and produce digestate derived compost of higher quality in an existing regional equipment.

Object of the case study – municipal BDW management system on the region level. One of the Lithuanian regions with centralised MBT, incl. intensive anaerobic treatment of BDW in dry fermentation tunnels, was selected for more detailed analysis.

Goal of the research: to suggest and evaluate alternatives for optimization of the municipal BDW management system in order to increase biogas output and/or nutrient recovery.

2. Materials and methods

2.1. Characteristics of the object

The research was carried out in one of Lithuanian regions (with a population of approx. 140 thousand residents), with developing tourism sector. The target region is characterised by numerous natural heritage objects (national parks, regional parks, nature reserves, etc.). The developed tourism sector greatly affects BDW content in mixed municipal waste (MMW) stream; it can reach up to 71.9 %, however, a significant fluctuation of BDW content is being observed due to seasonality.

Municipal BDW management system of selected Lithuanian region is analysed in this research. About 50 thousand tonnes of MSW are generated in the target region., incl. over 30 thousand tonnes of MMW, which is collected by a container system, and transported to a centralised MBT plant for processing (installed capacity – over 40 thousand tonnes per years of MMW). In the MBT, MMW is mechanically treated with a purpose to separate following fractions: secondary raw materials, refuse-derived fuel, and BDW. The separated BDW is anaerobically treated in dry fermentation tunnels (installed capacity – up to 15 thousand per year of BDW). Produced biogas is burned in cogeneration equipment (CE), while generated digestate (remaining solid material) is composted in the same tunnels and maturated within 2 months.

Since 2014, 8.5 thousand composting bins (containers) for green waste home composting have been distributed for individual houses. According to the results of monitoring and theoretical calculations [16], over 3 thousand tonnes per year of BDW can be composted in these containers. In addition, 4 centralised composting sites have been successfully working in this region. For example, in 2016, approx. 4.7 thousand tonnes of green waste from public territories were collected and aerobically treated. A part of produced compost has already been used for public territory greening.

Individual households of the target region were chosen for the first evaluation and implementation. Over 50 % of MMW, generated in the region, incl. up to 7.3 thousand tonnes per year of food waste can be collected using a two-sise container system: a smaller one (V: 5–10 l) can be used inside the house and a bigger one (V: 50–500 l) outside. Biodegradable bags can asists while collecting food waste.

The experiment with anaerobic treatment of source separated municipal food waste (from individual households and several catering companies) in one of the current fermentation tunnels (Bekon technology) of the centralised MBT plant was carried out within three months, incl. maturation of the primary compost. The evaluation of monitoring data shows that in case of fermentation of source separated food waste, a total biogas output in the MBT is increased up to 114.24 nm^3 per tonne of BDW, energy potential – up to 693 kWh per tonne of BDW, incl. electricity output – up to 204.4 kWh, heat energy – up to 384.6 kWh.

A source separated food waste collection and centralised treatment must meet the requirements presented in regulation (EC) No 1069/2009 of the European Parliament and of the Council. This is because this waste is considered as Category III Animal by-products (ABPs), and, therefore, must be managed in compliance with Regulation (EU) No 142/2011 requirements. In terms of collection, in case of temperature ≥+7 °C, ABPs can be stored for no longer than 3 days in special containers. Concerning treatment, the regulation requires a biogas production company to have a pasteurization/hygienisation and treat Category III ABPs ensuring the given technological parameters. For example, the main requirement for hygienisation of ABPs are following: maximum particle size of BDW before entering the unit – 12 mm, the minimum temperature in the unit – 70 °C, minimum time in the unit without interruption – 60 minutes. In case of pasteurization or sterilization: maximum particle size of BDW – 50 mm, temperature – 133 °C for at least 20 minutes without interruption at a pressure (absolute) of at least 3 bars.

2.2. Applied methods

Several different methods were applied in the research as the most suitable for the case. The methods are as follows:

- Analysis of scientific and practical literature;
- Quantification of MSW flows in the target region (statistical data presented by the regional waste management center);
- Evaluation of the composition of mixed municipal waste (MMW) flows (a mass balance principle);
- Material and energy flow analysis;
- Formation of fuel and energy balance;
- Evaluation of relative environmental indicators (energy output, biogas output, etc.).

The experiment with fermentation of source separated municipal BDW in one of the current fermentation tunnels was carried out within three months in summer. The purpose of the experiment was to evaluate average biogas output and energy potential. Finally, the data was monitored and systemised using relative environmental indicator.

The following equation was used for the evaluation of energetic value of generated biogas:

$$q = \frac{q_e + q_h + q_L}{3.6} \quad (1)$$

where

$q_{e.}$ produced electricity, MWh per analysed period (readings of an electric meter);

q_h produced heat energy, MWh per analysed period (meter readings of thermal energy);

q_L energy losses, MWh per analysed period (data from technical documentation of CE).

Energy potential of BDW or value of total energy output of BDW fermentation process was evaluated by using the following equation:

$$Q = \frac{q}{m} \quad (2)$$

where

q energetic value of combusted biogas, MWh per analysed period;

m mass of treated BDW, tonnes per analysed period.

The biogas output is calculated according to the following equation:

$$B = \frac{V}{m} \quad (3)$$

where

V volume of produced biogas, m^3 per analysed period;

m mass of treated BDW, tonnes per analysed period.

Such relative indicators as biogas output, electricity, heat or total energy production and consumption per tonne of BDW were used for a further feasibility analysis (environmental and economic evaluation) of a suggested alternative. IPCC Guidelines for National Greenhouse Gas Inventories and EMEP/EEA Air Pollutant Emission Inventory Guidebook was used to evaluate air emissions and GHGs generated by the MBT activity in term of the direct and indirect impact.

3. Results and discussion

3.1. Problem identification of existing municipal BDW management

The material and energy flow analysis of the current MBT plant was done during April 2017, when the fermentation equipment operated at full capacity. The data was evaluated by applying relative environmental indicators and is presented in Table 1. The equipment was able to produce only 24.21 nm^3 per tonne of BDW leading to minor excess electricity and heat energy generation (0.97 kWh per tonne of BDW). The electricity output of 41.33 kWh did not correspond with typical (75–225 kWh per tonne of BDW) electricity output presented in scientific literature [24, 25]. In comparison, one year ago, a volume of biogas output was only 17.31 nm^3 per tonne of BDW. This value was taken as the most pessimistic value while evaluating biogas output from mechanically recovered BDW from MMW in the alternative feasibility analysis.

Table 1. Fuel energy balance of the current MBT plant.

Parameters of BDW		Dimensions, units per tonne of BDW	Current situation
1		2	3
Biogas output (BDW from MMW)		m^3	24.21
Biogas output (source separated FW)		m^3	0
Energy output (100 %), incl.		kWh	140.41
	electricity output	kWh	41.33
	thermal energy output	kWh	78.01
	energy losses	kWh	21.07
Electricity consumption		kWh	40.64
Thermal energy consumption		kWh	77.73
Diesel fuel consumption		kWh	6.3
Excess electricity		kWh	0.69
Excess thermal energy		kWh	0.28
Energy balance		**kWh**	**–5.33**

In case of the evaluation of diesel fuel consumption in the MBT plant, negative volume – –5.33 kWh per tonne of BDW in the total energy balance was observed. In addition, about 0.87 tonnes of diesel fuel or 36.63 MJ per tonne of MMW were used for transportation to the MBT territory.

During mechanically recovered municipal BDW processing in the MBT, the produced Technical compost contains large amounts of contaminants. This compost (stabilate) is characterised by rather high concentration of heavy metals, organic and inorganic impurities, sulphates and chlorides, and a small volume of organic matter. As a result, it can be used for overlay of landfill layers. However, the quantity of the stabilate is already exceeded demand for the overlaying. For this reason, a part of the stabilate is being disposed in a landfill as waste which immobilises nutrients.

3.2. Increasing alternative energy production by optimization of existing municipal BDW management

Various methods can be used to increase biogas output from BDW. For instance, by adding 2 mg/kg (dry material) of selenium can foster propionic acid oxidation and, therefore, increase biogas production by 60–70 % [26]. In contrast, supplementation of iron, nickel, and cobalt separately can increase biogas production up to 34 % [26]. In addition, these metals consumption can be reduced by dosage of ethylenediaminetetraacetic acid which increases bio-availability of the metals [26]. The application of pre-treatment methods contributes to biogas output increase as well, but varies greatly. For example, the pre-treatment with hydrochloric acid would increase biogas generation up to 30 %, while high voltage pulse discharges up to 134 % [20, 21]. However, all these methods are energy-intensive, moreover, the quality of produced technical compost remains poor or even worse, suspending nutrients inside to be recycled in agriculture [14].

Some researches emphasise fact that a MSW management system should be customised to a specific region in order to deliver the best performance and minimum environmental impact [17]. Measures for BDW management optimization such as BDW (e.g. food waste) source separation from the MSW steam have a strong background in the target region. As a result, a source separation was chosen for further evaluation. The assumption was made that food waste can be separated by the efficiency of 80 % and then diverted to the territory of the existing centralised MBT plant. 2–3 routes per week for this collection of waste is necessary to comply with the animal by-products regulation. However, the increased number of routes will not significantly affect diesel fuel consumption. It was evaluated that approx. 5.47 tonnes of diesel fuel will be used for food waste delivery to MBT, while 5.1 tonnes of diesel per year will be saved due to a reduction of remaining MSW. To ensure the compliance to the Regulation (EU) No 142/2011, a hygienisation technological line with the precrusher and sterilization tank with capacity of 3.5 tonnes per hour of BDW was selected. As the installed electric power of such equipment is 35 kW, electricity consumption within MBT plant would be increased by 44 MWh per year. BDW would be treated mechanically to remove impurities prior to the biological treatment. 2–3 tunnels of the existing biological treatment would be used for anaerobic fermentation and aerobic composting of food waste after hygienisation. The remaining volume of municipal BDW (up to 8.8 thousand tonnes per year) would be transported to the MBT plant with MMW stream and managed as usual. Biogas output of such BDW after mechanical separation is approx. 17–18 nm^3 per tonne of BDW, and energy potential is significantly decreased.

The implementation of the alternative would allow saving up to 128.7 thousand EUR per year (see Table 2). Total project investment (including designing work, installation of ABPs sterilization line (for example, “MAVITEC Green energy”), and special containers for municipal food waste source separation (V: 50–100 l) (up to 39700 units)) is approx. 676 thousand EUR. The project pay-back period is approximately 5.3 years.

Table 2. Evaluation of saving after the implementation of the alternative [29].

		Current situation	Planned situation	Savings / income	
	Dimensions	Units per year	Units per year	Units per year	EUR per year
Diesel fuel consumption for transportation waste[1]	tonnes	26.21	26.58	–0.37	–837.00
Diesel fuel consumption in MBT	tonnes	7.9	7.72	0.18	163.00
Excess electricity production	MWh	10.35	880.42	870.07	32001.00
Excess thermal energy production	MWh	4.2	1720.53	1716.33	61788.00
Probiotic consumption[2]	l	80	47	33	396.00
Compost production	tonnes	0	2930	2930	35160.00
Stabilate	tonnes	6500	3820	2680	
Air emissions (CO, NO_x, NMVOC, PM, NH_3)	tonnes	7.73	8.06	–0.33	
				SUM	128671.00

Note: [1]Price of diesel fuel is 0.76 EUR per liter without VAT; according to monitoring data, expenditures for fuel make up to 40 % of total transportation costs.
[2]Probiotic is used within BDW aerobic treatment process for minimization of risk of microbiological contamination.

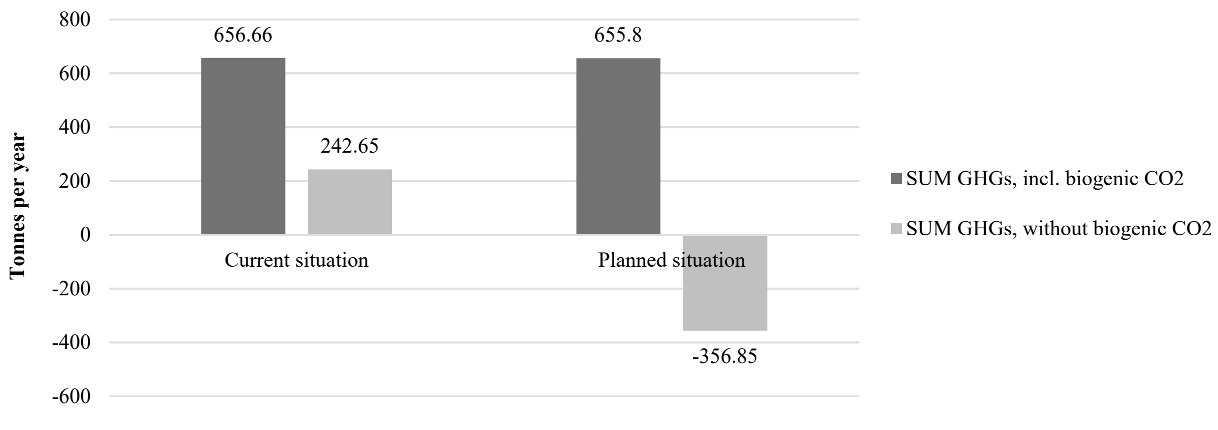

Fig. 1. Comparison of GHGs before and after the implementation of the alternative.

The alternative would allow not only increasing biogas output by 2.5 times but also producing higher quality compost instead of only suitable for landfill overlaying, thus, implementing sustainable resource management highlighted in many scientific articles [30]. Regarding environmental impact, air emissions and GHGs of the existing plant and proposed alternative were evaluated and compared. The results of the comparative analysis shown that air emissions would slightly increase after the implementation of the alternative. The reason is the increase of diesel fuel consumption for the separated food waste collection and volume of combusted biogas (by 2.25 times).

Regarding GHGs, the amounts of GHGs without and including biogenic CO_2 were analysed. In case of biogenic CO_2, after the implementation of the alternative the amount of GHGs decreases just by 0.86 tonnes per year. If biogenic CO_2 was not taken into account, GHGs emissions would be reduced by 599.5 tonnes per year (see Fig. 1).

In terms of nutrients recovery, stabilate production suitable only for landfill overlaying, would be decreased by 1.7 times. In the planned alternative, 2930 tonnes per year of relatively good quality compost from source separated municipal food waste would be produced in the existing MBT. Such compost can be successfully used for growing energetic plants, land restoration, etc, thus, promoting bio-resources efficiency [16–18, 31].

Table 3. Energy balance of MMW management before and after the alternative implementation.

	Current situation	Planned situation	Increase (–)/decrease (+)
	GJ per year	GJ per year	GJ per year
Consumption			
Diesel fuel	1469.11	1477.3	–8.19
Electricity	2194.56	2301.77	–107.21
Thermal energy	4197.6	4099.5	98.1
SUM	**7861.27**	**7878.57**	–17.30
Production			
Electricity	2231.82	5471.28	3239.46
Thermal energy	4212.54	10293.41	6080.87
SUM	**6444.36**	**15764.69**	9320.33
Total energy balance	**–1416.91**	**7886.12**	9303.03

The implementation of the suggested alternative would slightly affect energy consumption, yet there would be significant increase in energy production (see Table 3). The energy consumption increase would constitute only 17.30 GJ per year, but energy production would exceed consumption nearly two-fold. After the implementation of the suggested alternative, the total balance would be higher than the existing one by 9303 GJ per year (see Table 3).

4. Conclusion

- The following environmental and, thus, economic problems were identified in analysed region municipal BDW management system: biogas output within the centralised MBT plant with anaerobic treatment of municipal BDW constitutes only 24.21 nm^3 per tonne of BDW; energy consumption during MMW treatment in the MBT plant exceeds energy production by 5.33 kWh per tonne of BDW; produced compost (stabilised BDW) is contaminated with heavy metals, impurities, and microbiological contamination. Therefore, the compost was used only for overlaying the landfill;
- Several alternatives were suggested for the optimization of the existing centralised municipal BDW management to increase biogas output and nutrient recovery. The feasibility analysis of suggested alternatives determined that source separation of BDW from MMW is the best available for this region due to rather substantial volume of BDW in the MSW stream, and rapid growth of tourism sector. Furthermore, the generation of MMW is concentrated across several big cities. Therefore, source separation is reasonable due to the minimum increase of diesel fuel consumption;
- The implementation of THE suggested alternative would allow increasing biogas output by 4.7 times, alternative energy production – by 4.9 times, excess energy production in the existing MBT plant – by 2586 MWh per year (or by 86.2 kWh per tonne of BDW), and minimizing stabile production by 2.59 thousand tonnes per year. The

total energy balance of MMW management would be positive (≈7.8 TJ per year) due to the minimization of diesel fuel consumption for MMW transportation and increasing alternative energy production within the centralised MBT equipment. Regarding environmental impact, if suggested alternative was applied, GHGs (without biogenic CO_2) would be decreased by 599.5 tonnes per year.

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