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EVALUATION OF THE ECOLOGICAL EFFECT OF BIODEGRADABLE WASTE PROCESSING IN A COMPREHENSIVE MUNICIPAL WASTE MANAGEMENT SYSTEM

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Abstract
Recycling of biodegradable waste is one of the trends in the recovery of organic matter together with its use for reclamation, but most importantly the reduction of biodegradable waste and the reduction of waste for disposal. The paper presents the use of the decision analysis method in the selection of the most advantageous organic recycling solution in a large agglomeration. The proposed method uses the tool of life cycle analysis (LCA) and decisional analysis.

Keywords: **Municipal biodegradable waste; Composting, methane fermentation; LCA analysis; Decision analysis.**

1. INTRODUCTION

A properly managed municipal waste management system allows for the processing of all waste streams, including organic waste, which is one of the significant components of the entire stream. This should be done in accordance with the waste management hierarchy provided for in the Waste Framework Directive 2008/98/EC [1] and amended by 2018/851/EC [2]. In accordance with its provisions, Member States should introduce measures to promote the prevention and reduction of food waste, and in particular, by 2030, halve the global amount of food waste per capita in retail and consumption, reduce food losses in the production and distribution process. Member States should aim to achieve the Union indicative target of a 30% reduction of food waste by 2025 and 50% by 2030. In addition, in the light of the provisions of the Landfill Directive(1999/31/EC) [3]. Member States should develop a national strategy to reduce the amount of biodegradable waste going to landfill. The strategy must ensure a certain degree of reduction of the amount of municipal waste in relation to the level of production in 1995. The levels of reduction of biodegradable waste should be ensured in such a way that no later than 15 years after the introduction of the provisions of the Directive, municipal biodegradable waste intended for landfills is reduced to 35% of the total weight of waste produced in 1995 [4–7].

2. ORGANIC WASTE SOURCES AND RECYCLING

According to the Central Statistical Office, in 2017 a total of 11,97 million Mg of municipal waste was collected in Poland, both selectively collected and mixed. About 7.5% of this value was made up of selectively collected biodegradable waste (895 thousand Mg). Most of the 811 thousand Mg of biodegradable waste collected in 2017 came from households (90.5%). The remaining biodegradable waste came from sources other than households, i.e. municipal services, trade, small business, offices and institutions (in total about 85 thousand Mg). According to the data of the Central Statistical Office (GUS) from 2018, a total of 11 969 thousand Mg of waste was collected in Poland, including 848 thousand Mg of composting or fermentation processes [8].

In 1995, which is the comparative year, 4.381 million Mg of biodegradable municipal waste was produced, with 155 kg per city inhabitant and 47 kg per rural inhabitant. According to EU data from 2010, on average more than 89 000 Mg was produced in Europe, of which more than 34 000 Mg came from industry, more than 37 000 Mg from households and more than 16 000 Mg from other sources [9].

The need to treat organic waste and the ban on landfill results from the need to reduce greenhouse gases to the environment. Organic recovery and recycling must therefore be applied. According to the law, recovery is any process whose main result is that waste serves a useful purpose by replacing other materials which would otherwise be used to fulfil a given function, or by which waste is prepared to fulfil such a function in a given plant or in the economy in general. Recycling, including organic recycling but not including energy recovery and reprocessing into materials to be used as fuels or for backfilling operations, is also one form of recovery. Among the organic recycling methods, it stands out:

- methane fermentation – anaerobic process of decomposition (mineralization) of complex macromolecular organic substances contained in biomass, leading to stabilization of biomass properties [10–15] [16–18],
- composting – aerobic treatment of organic waste, based on natural biochemical reactions, intensified under artificially created optimal conditions, ensuring its control [10–13] [16–18].

The organic waste treatment processes also cause emissions to the environment [14–15]. Therefore, the aim of the paper will be an attempt to compare the emissions arising from various processes of biodegradable waste processing. Life cycle analysis is often used for this kind of assessments. Life Cycle Assessment (LCA) [20–24] – a relatively new environmental management technique, assessing the environmental impact of products, techniques, technologies or activities during the whole life cycle at particular stages; it is based on ecobalances (materials used, raw materials, energy and emissions received) of the assessed products or technologies, which result in environmental assessment in the form of environmental impact categories or so-called areas of damage defined as: system quality, human health and resource consumption [25–28]. The LCA methodology has found its recognition in the environmental management standards ISO 14000 [29–32]. In the field of waste management, specialist softwares were developed, and used to calculate the environmental load. The most important of them include: EASEWASTE (Environmental Assessment of Solid Waste System and Technologies), developed by the Technical University of Denmark [33], IWM (currently IWM – 2) developed by Procter & Gamble, for the assessment of municipal waste management systems [14, 20, 34], WRATE (Waste and Resources Assessment Tool for the Environment) [35], Integrated Waste Model (IWM) site at the University of Waterloo [33].

3. ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF WASTE MANAGEMENT SYSTEMS – PROPOSED METHODOLOGY – CALCULATION METHODOLOGY

The aim of this paper is to present the method of analysis and selection of the system of management of the biodegradable household arising as one of the streams. In the justification of taking into account only the ecological factor of the discussed systems, it should be noted that in their design and analysis the most difficult and controversial aspect is this factor. It affects both the economic factor (increasing costs of waste processing and protection of the environment against the influence of the installation) and the social factor (fears of the inhabitants of the environmental impact and health and life). Thus, the following stages can be distinguished in the proposed method:

- development of waste management system variants considering various technologies of biodegradable waste processing,
- the quantitative and qualitative balance of the individual waste streams generated in the region, including organic recycling methods,
- calculation and assessment of emissions from individual options,
- decision analysis and selection of a system that will have the least possible impact on the environment.

The Integrated Waste Model (IWM – 2), developed by Procetr&Gamble for the environmental assessment of waste and packaging management systems [24, 28, 31, 35], was used to determine the ecological effects of waste management systems in the region. The model is based on the LCA (Life Cycle Inventory) analysis and uses its first stage: LCI (Life Cycle Inventory), i.e. determination of sets of inputs and outputs from the analysed waste management system (system balance analysis – data inventory). Transparency of the model allows to track changes at each stage of calculations in the scope of both waste stream balancing and emissions not only from the whole system, but also from individual unit processes. The functional unit of this model is a comprehensive system of municipal waste management in a specific geographical region and at a specific time. The result obtained in the form of emissions from the system will constitute a decision-making matrix and a defined decision-making problem.

A multi-criteria analysis was also used to select the most advantageous waste management system in terms of environmental impact. For the analysis, the waste management scenarios described and balanced in detail in the IWM – 2 programme were adopted. Since the decision-making task was to select the variant which would have the least impact on the environment, the assessment criteria are the values of emissions to the environment, recorded in groups:

– the final stream of waste generated as a result of the operation of individual variant solutions
– emissions to air
– emissions to water, as a result of the operation of the different system options.

The distinction between groups of criteria allows for weighting of individual groups of criteria or individual criteria. For multi-criteria analysis the weighted sum method was used. To solve the decision-making task, the compromise programming method was used, using the concept of ordering individual technology variants according to their distance from a fixed ideal point $X'(x_1', x_2', ..., x_M')$, whose all x_M' coordinates are equal to the maximum value of the adopted standardization scale. The mathematical record of the measure of the distance of the tested variant from the ideal point has the form [24, 28]:

$$L_\alpha(s_n) = \sum_{m=1}^{M} w_m^\alpha \, (x'_m - r'_{NM})^\alpha \qquad (1)$$

and the choice of the most advantageous solution is made according to the principle:

$$s_j = s \Leftrightarrow L_\alpha(s_j) = min L_\alpha(s_n); \;\; n = 1, 2, \dots, N \quad (2)$$

where:

sj – measure of the difference between a given s_n variant and an ideal point

s – the chosen option,

w_m – weighting factor of criterion m,

x_m' – m – that coordinate of the ideal point,

r_{NM}' – standardised value of the assessment criterion,

M – number of criteria,

α – a power factor measuring the deviation of the strategy from the ideal point X', taken in practice as 1, 2 and ∞.

The final solution when using multi-criteria analysis is to rank the variants of waste management system solutions from the most to the least beneficial for the natural environment.

4. ASSESSMENT OF THE ENVIRONMENTAL IMPACT OF WASTE MANAGEMENT SYSTEMS – PROPOSED METHODOLOGY – CASE STUDY

The aim of this task will be to select the most environmentally beneficial solution for organic recycling in a comprehensive waste management system in the selected region. Among the most important assumptions for the calculation one should specify [35]:

– Municipality adopted for the calculation – 900,000 inhabitants, average waste accumulation rate of 326 kg/ M per year; for waste morphology: paper – 19.5%, glass – 9%, metal – 2.5%, plastics – 17.6%, textiles – 3.3%, biodegradable waste – 40%, other waste – 8.1%. A part of municipal waste (secondary raw materials and green waste) will be collected in the system of delivery to the collection point. Additionally, it was assumed that waste from the infrastructure will be collected in the amount of about 500 Mg per year. The Program contains detailed balances of all the waste streams generated in terms of their quantity and quality.
– Three scenarios for the functioning of the waste management system were assumed, all based on and segregation of utility fractions and green waste and their processing. Organic recycling methods vary; for comparison of these systems and emissions from them, it is assumed that the remaining elements, recovery and recycling do not change.
– In the first “biodegr1” scenario, it was assumed that organic waste would be processed in composting processes, with over 286 thousand Mg of waste per year, the biodegradable fraction would be separated in the amount of over 55 thousand Mg and subjected to the composting process.
– In the second “biodegr2” scenario, it is assumed that organic waste in the same amount will undergo the process of methane fermentation using energy,
– The third analysed “biodegr3” scenario assumes

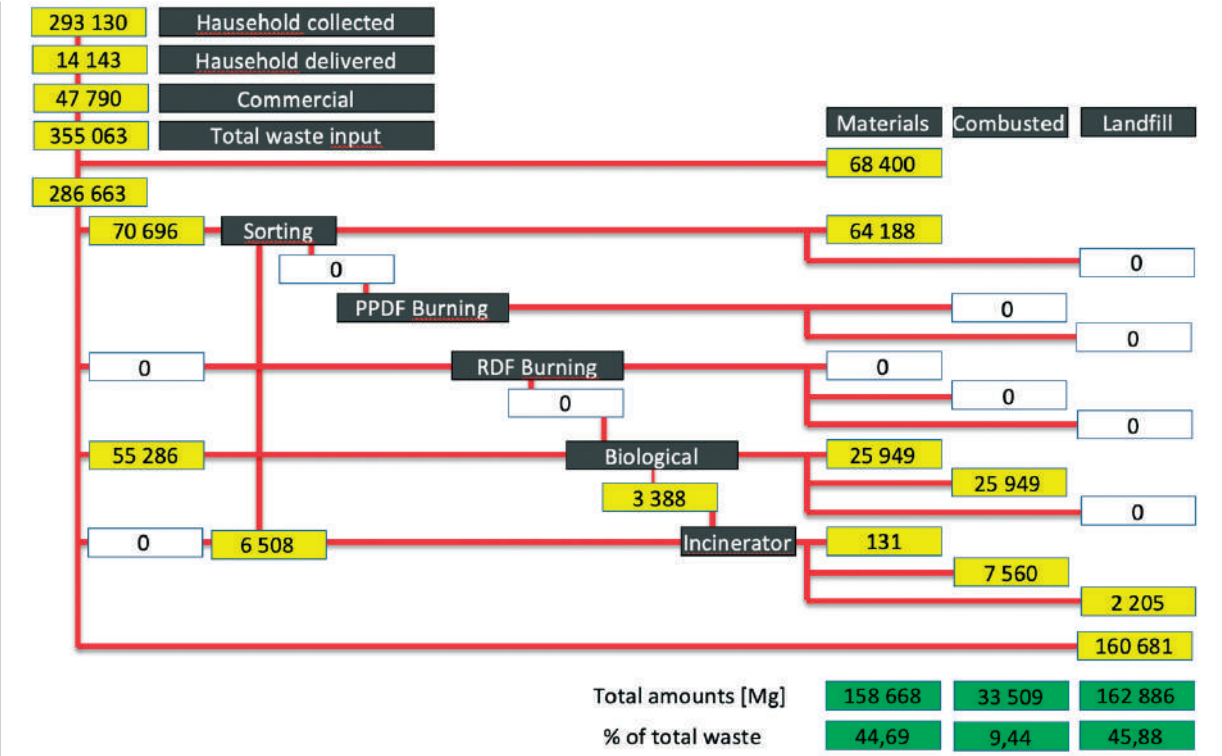

Figure 1.
Diagram showing mass flows and structure of waste management system – Scenario "biodegr1" [31]

that organic waste will be deposited in a landfill and 50% of the energy from biogas production will be used.

– Costs were not taken into account in the analysis, as economic analysis was not the purpose of this paper.

On the basis of the adopted assumptions, the program generated the previously described waste management scenarios, presenting them in the form of diagrams showing the functioning of individual systems and flows of individual waste streams. The comprehensive diagram is presented in Figure 1. The figure in the "yellow" boxes shows mass flows of waste expressed in [Mg/year], on the left side "entering the system", on the right side "leaving" the waste quantity system. In the "black" boxes the descriptions of waste streams flowing through the system are presented, therefore they should be referred to the yellow "boxes". The "green" windows at the bottom of the diagram show the total waste streams leaving the system: the stream of raw materials (materials) recovered from waste, the level of weight reduction as a result of waste treatment (e.g. moisture loss) and the remaining amount of treated waste that must be directed to landfill. These values are expressed in [Mg] and [% weight].

The results obtained from the IWM – 2 programme are the emissions to the environment as a result of the operation of individual scenarios. Emissions are presented at individual stages of system operation (as a result of the operation of each installation) and for each environmental component separately: solid waste emissions, emissions to air and emissions to water; additionally, they are broken down into individual chemical compounds. The decision problem is formulated when the assessment criteria are established and their values expressed in the form of a finite set of numbers (measurable values), resulting from the assessment of individual variants of the waste management system in the same municipality, against selected criteria. The total emissions obtained as a result of the operation of particular waste management scenarios listed in the table may constitute a decision matrix for the selection of the most environmentally beneficial system solution. The columns of Table 1 present the values of emissions to the environment calculated from particular variants, compiled in three groups of impact on particular elements of the environment.

Table 1.
Decision matrix for evaluation of the adopted scenarios of the waste management system [own elaboration, 31]

Groups of criteria	Evaluation criteria	Unit	Scenarios assessed		
			biodegr1	biodegr2	biodegr3
Products of waste system	non-hazardous waste	Mg	162 569	186 459	217 598
	hazardous waste	Mg	317	208	208
	industrial-energy	Mg	-23 101	-23 712	-21 899
	recycling-credits	Mg	-129 723	-129 723	-129 723
Air emissions	particulates	g	-60 161 582	-65 757 552	-49 176 364
	CO	g	160 567 680	162 035 402	145 164 114
	CO_2	g	-758 914 414	-7 061 853 481	-9 646 142 425
	CH_4	g	2 142 330 146	2 320 763 312	16 178 043 617
	NO_x	g	-102 528 671	-109 811 233	-81 752 094
	N_2O	g	-633 126	1 101 062	1 236 175
	SO_x	g	-249 365 503	-272 513 715	-199 511 206
	HCl	g	-4 281 514	-4 980 049	-556 576
	HF	g	93 730	19 611	720 604
	H_2S	g	1 228 962	1 327 654	8 355 604
	Total HC	g	12 523 251	13 602 420	82 521 690
	Chlorinated HC	g	419 299	455 463	1 444 130
	dioxins/furans	g	0	0	0
	Ammonia	g	2 937 333	3 832 925	3 872 407
	Arsenic	g	-1 560 333	-1 560 333	-1 560 333
	Cadmium	g	-951	-1053	-565
	Chromium	g	215	210	233
	Copper	g	1 047	1 047	1 047
	Lead	g	1 205 393	1 204 353	1 207 526
	Manganese	g	-2 099	-2 524	-1 235
	Mercury	g	-316	-505	-110
	Nickel	g	-35 957	-42 267	-23 613
	Zinc	g	-7 358	-8 817	-1 879
Emissions of waste water	BOD	g	70 393 135	67 312 076	71 248 274
	COD	g	-2 005 889 375	-2 009 094 680	-2 007 898 957
	Suspended Solids	g	-38 518 036	-40 000 836	-35 420 622
	TOC	g	128 014 859	127 677 491	128 704 596
	AOX	g	-20 863 146	-20 862 465	-20 859 710
	Chlorinated HC	g	6 731	6 930	8 475
	Phenols	g	-32 196	-34 557	-26 565
	Aluminium	g	-14 759 197	-16 711 297	-10 792 694
	Ammonium	g	548 415	1 292 002	-66 477
	Arsenic	g	-31 849	-35 744	-23 899
	Barium	g	-1 374 011	-1 569 423	-976 947
	Cadmium	g	-2 035	-2 160	-1 754
	Chloride	g	478 353 071	457 092 551	522 539 566
	Chromium	g	-163 046	-182 426	-123 492
	Copper	g	-40 295	-49 863	-20 702
	Cyanide	g	-59 138 643	-59 138 772	-59 138 382
	Fluoride	g	631	747	1 267
	Iron	g	-11 899 310	-14 502 753	-6 430 090
	Lead	g	-94 632	-106 416	-70 556
	Mercury	g	73	70	81

Emissions of waste water	Nickel	g	-78 773	-88 442	-58 656
	Nitrate	g	36 371 903	36 314 673	36 488 189
	Phosphate	g	9 151	-105 730	242 579
	Sulphate	g	219 415 514	197 393 850	264 188 556
	Sulphide	g	-508	-1 084	664
	Zinc	g	-147 160	-166 503	-106 209

The matrix formulated in this way has become a formulated decision problem to be solved using the formula-weighted sum method (1) and (2). The compromise programming method gives complex results due to the possibility for the evaluator to weight individual evaluation criteria and to introduce additional weighting by introducing the coefficient . The results and the final arrangement of individual solutions of the waste management system are presented in Table 2, ranked from the most favourable to the least favourable. The ranking additionally depends on the adopted weights of particular groups of criteria or particular criteria. Table 2 in the first column presents the weights of the criteria proposed by the author of the study. In most cases, these weights were given to the groups of criteria described in Table 1. Thus, in the first row of Table 2, all the criteria were given a weighting of 1, while in the second row, the first group of criteria (waste resulting from the operation of the scenarios) received a weighting of 2, while the remaining two groups received a weighting of 1. In the last row of Table 2, only two evaluation criteria received a weighting higher than the others. These were the air emissions "CO_2" and "CH_4". With such weights and values of the assessment criteria, the result presented in Table 2 was obtained.

On the basis of the assumptions and calculations it was found:

– in 39 cases, methane fermentation, which allows for recovery and use of energy from waste and organic material for reclamation, is always chosen as the most beneficial solution from an environmental point of view.

– Composting is always chosen as the second most environmentally beneficial solution as an organic recycling method allowing only organic material to be used for reclamation.

– The least used is always the landfill of waste with the use of energy and potentially the greatest environmental impact.

– In some cases, where $\alpha = \infty$, organic recycling solutions: composting and fermentation are chosen as equivalent solutions, this is the case when the highest weights are given to the waste or air emission criteria groups.

Table 2.
Arrangement of individual scenarios of waste management system solutions

Weight of the criteria	Ranking of options for waste management systems with different organic recycling technologies		
	$\alpha = 1$	$\alpha = 2$	$\alpha = \infty$
01:01:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3
02:01:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
01:02:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2
01:01:02	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
05:01:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
01:05:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
01:01:05	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
01:02:02	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
01:05:05	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
02:01:02	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
05:01:05	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3
02:02:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1
05:05:01	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3	biodegr2→biodegr1→biodegr3

5. SUMMARY AND CONCLUSIONS

- Organic waste is always produced as part of the municipal waste stream. In communes with a typically urban character there are more of them, even up to 40–50 % of the total stream. In communes of a rural character, there are fewer of them, even up to about 15% of the mass, but it happens that the characteristics of waste from rural areas are similar to those of waste from cities. Bio-waste tends to be quickly compacted, resulting in a significant nuisance and threat to people and the environment.
- Reducing the negative impact requires segregation, treatment and, where possible, use of process products. This will eliminate the negative impact on the environment and at the same time improve it through e.g. reclamation of degraded areas. The collection and proper processing of organic waste should ensure: the production of fully-value organic material that can be used or safely stored in a landfill; reduction of the volume of organic waste to about 50% and elimination of processes that take place in untreated waste.
- The use of decision analysis for comparison and decision making in the area of broadly understood municipal management provides a tool for decision makers. It allows for objective assessment and selection of the most beneficial solution for the natural environment.

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