ECOLOGY

UDC 504.062.2
DOI: 10.15587/1729-4061.2023.273930

INTEGRATED METHOD FOR PLANNING WASTE MANAGEMENT BASED ON THE MATERIAL FLOW ANALYSIS AND LIFE CYCLE ASSESSMENT

Vladyslav Bendiuh
Corresponding author
PhD, Associate Professor
Department of Mathematical Methods of System Analysis*
E-mail: vladyslavbendiuh@gmail.com
Liudmyla Markina
Doctor of Technical Sciences, Professor**
Nataliia Matsai
PhD, Associate Professor, Dean
Faculty of Natural Sciences***
Iryna Kyrpychova
PhD, Associate Professor
Department of Horticulture and Ecology***
Sergii Boichenko
Doctor of Technical Sciences, Professor, Head of Department
Department of Automation of Electrical and Mechatronic Complexes*
Serhii Priadko
Senior Lecturer
Department of Automation of Electrical and Mechatronic Complexes*
Iryna Shkilniuk
PhD, Head of Department
Department of Automation of Electrical and Mechatronic Complexes*
Bohdana Komarysta
PhD, Associate Professor
Department of Mathematical Methods of System Analysis*
Iryna Yermakovych
PhD, Associate Professor
Department Animal Health and Ecology
Volodymyr Dahl East Ukrainian National University
Tsentralniy ave., 59-a, Severodonetsk, Ukraine, 93400
Oleh Vlasenko
Researcher, Postgraduate Student**
*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Peremohy ave., 37, Kyiv, Ukraine, 03056
**Department of Environmental Audit and Environmental Protection Technologies
State Ecological Academy of Postgraduate Education and Management
Mytropolyta Vasylia Lypkivskoho str., 35, Kyiv, Ukraine, 03035
***Luhansk Taras Shevchenko National University
Kovalia str., 3, Poltava, Ukraine, 36003

This paper gives a solution to the problem of improving a solid waste management system through the integration of two systemic methodologies: material flow analysis and life cycle assessment. The proposed method serves to assess the effectiveness of the implementation of various waste management measures.

The study was carried out with the detailing of the anaerobic digestion process since it is this recycling technology that plays a key role in reducing the amount of waste along with the production of renewable energy and in reducing the adverse effects on the external environment.

Simulation of changes in waste properties in a certain processing sequence was carried out in order to obtain reliable information for further optimization of the system. The proposed modeling of waste treatment processes based on their constituent equations made it possible to adequately reflect the impact of changes in working conditions on all subsequent output flows.

The analysis of material flows for an enterprise of mechanical and biological treatment of waste is presented and the use of the model in the context of the process of anaerobic digestion of household waste is illustrated. It was found that anaerobic digestion potentially makes it possible to obtain 4.1 Gj of biogas energy from 1 HSW, which corresponds to 460 kWh of electricity and 2060 MJ of heat.

The developed method is based on a combination of analysis of material flows and life cycle assessment. The method acts as a tool for comparing alternative technologies and waste management scenarios. In the future, it can serve to support waste management decisions at both the strategic and operational levels

Keywords: household waste, material flow analysis, life cycle assessment, anaerobic digestion

Received date 01.12.2022
Accepted date 06.02.2023
Published date 28.02.2023

How to Cite: *Bendiuh, V., Markina, L., Matsai, N., Kyrpychova, I., Boichenko, S., Priadko, S., Shkilniuk, I., Komarysta, B., Yermakovych, I., Vlasenko, O. (2023). Integrated method for planning waste management based on the material flow analysis and life cycle assessment. Eastern-European Journal of Enterprise Technologies, 1 (10 (121)), 6–18. doi: https://doi.org/10.15587/1729-4061.2023.273930*

1. Introduction

The issue of technogenic waste management is of global importance for the preservation of the ecological system, so it is necessary to find new methods of replenishing or replacing consumed resources. It becomes obvious that it is necessary to reorganize the economy in such a way that human industrial activity is fully integrated into an effective environmental infrastructure.

One of such methods in the transport infrastructure is the introduction of recycling processes (for example, auto- and air recycling) [1] and waste disposal of the transport

Copyright © 2023, Authors. This is an open access article under the Creative Commons CC BY license

complex [2]. In the communal sector, examples include the conservation of water resources by purification (for example, from pharmaceuticals and biogenic elements [3]); in construction – renovation of buildings and structures. In agriculture, reuse is represented by the production of biofertilizers and biofuels by removing biogenic compounds from wastewater [4].

Waste management is reaching a new, high-quality level. More and more often there are statements about the birth of a new science – garbology (from English – "garbage" – garbage), or more simply – garbage disposal.

For the effective functioning of the waste management system at all its stages, an extensive network of facilities is being created in cities and regions. These are, in particular, sorting lines, garbage handling stations, recycling enterprises, each of which at the heart of its work has different technological aspects and different levels of operational productivity [5].

With such a variety of methods, there is a need for analytical tools that could be used to effectively select and combine them. A tool that would in complex interdependent systems, using a holistic systematic approach, would reflect this complexity of the relationship of system objects.

The main idea of the concept of a circular economy is the ability to achieve multi-vector goals of the economic development of territories, it provides conditions for the formation of a healthy nation by improving the ecological situation [6]. The principles of the circular economy change the paradigm in the field of household waste management, consider waste as a resource.

However, in order to assess the amount and potential of waste, to close production material cycles, there is a problem of lack of information. There are no indicators for accounting for waste flows, the potential for its processing, and the impact on the environment.

The lack of data leads to the adoption by responsible persons of erroneous decisions regarding the choice of waste management strategy by determining the directions for restoring resources that would allow them to benefit from them and reduce their excessive consumption.

Therefore, it is relevant to devise methods for analyzing and improving the solid waste management system, in which it would be possible to evaluate the flow of materials. At the same time, it is important to take into account the methods' ability to predict the impact of the addition of new technologies on the properties of flows and composition of the waste management system.

2. Literature review and problem statement

Several tools have been developed that aim at the effective selection of methods and technologies for household solid waste (HSW) management.

The most common models for evaluating a waste management system are Material Flow Analysis (MFA), Life Cycle Assessment (LCA), which are separate powerful assessment tools. However, their integration makes it possible to assess a comprehensive picture of the impact and comprehensively assess the potential of waste. The practice of combining methods for analyzing the flow of materials and substances with life cycle assessment already exists.

One of the first such studies in the field of waste management, where an MFA would be applied for further integration into the LCA was made to evaluate the compost production plant in Aarhus, Denmark [7]. In the study, samples were taken (eight times during the year) from the finished compost to obtain 5-gram laboratory samples for analysis. They were estimated by the mass content of substances; the cost of diesel fuel consumption of electricity is estimated. Nevertheless, the object of research is exclusively garden waste. Therefore, the considered method cannot be applied to the waste management system in other cities where either the entire stream of household solid waste or mixed organic matter should be recycled. In addition, according to the authors, the considered installation has a number of technological differences (high roll size (4–4.5 m) than is usually recommended (1.5–3 m), which can greatly affect the process. In addition, the rotational speed at the compost plant was very low (5–7 times a year), which could lead to long anaerobic periods, and therefore greatly distort the results. Therefore, more correct may be the study or operation of several installations, or imitation of the process in the laboratory.

In study [8], software was developed, the main purpose of which was to devise a holistic structure that would allow modeling highly heterogeneous material flows with large variations in physical and chemical properties. The new software allows the user to simulate the flow of materials and the impact of processing technologies. However, the model at the heart of the software [8] is based on several territorial assumptions that have a significant impact on the results and are specific to the country where the model was developed. Thus, it should be noted that the morphological composition of waste in terms of organic content is very different. The model also requires consideration of a significant amount of data to model the handling system, which means the importance of being able to assess the sustainability of results that technological specialists cannot always perform. Collecting large amounts of data in production is expensive and labor-intensive. Therefore, it can be argued that its application is not universal and there is a problem of developing a generally accepted model.

Of particular interest for the topic is study [9] conducted for the technological process of the plant of combined dry anaerobic digestion and post-compost treatment, located in the northern part of Germany. Based on the study, transmission coefficients for 21 waste substances were established. Potential areas of improvement of the facility were also highlighted, which showed that biogas production could potentially be increased from 50.7 nm^3 biogas/ton of waste received to 76.0 nm^3 biogas/ton of waste obtained if the capacity of anaerobic reactors is sufficient. However, the reported study due to the peculiarities of the plant's operation does not take into account the factor of waste pretreatment. Also, there is a deviation in the process of anaerobic digestion since the waste can be located for several days in an open area in the emergency room. This is due to the current insufficient capacity for anaerobic digestion reactors at the facility under consideration in the study. Anaerobic digestion reactors and composting reactors at the enterprise operate in a periodic mode. The peculiarity in the study is that the waste is not pre-processed before entering the reactors, and there is the presence of green waste in the waste structure [9]. Therefore, the study is not universal and cannot be widely used.

The most comprehensive is the study of 77 anaerobic digestion plants in Japan [10]. Attention was focused on total mass flows (waste, compost, and residues), heavy metals and fertilizer compounds; the mass-element balance of composting solid waste plants that process food waste.

The conclusions of the study implied that the performance of installations depends on the input material, and further research in this area should be focused on optimizing the operation of installations that process the same input material. Nevertheless, in general, balancing materials and substances turned out to be a difficult process due to the lack of completeness of parameters and the unreliability of heterogeneous data. The fact is that all installations have their characteristics and different principle of operation: 15 % operate on the principle of dryer, 35 % are autonomous composting plants, other objects used a standard composting process in the tank. However, they work on a different morphological composition of the material, combining not only household waste but also industrial waste and some wastewater.

Another significant drawback that occurs in scientific works is the failure to take into account energy consumption [11]. Energy is one of the biggest challenges in modeling waste management as it has a significant impact at all stages of waste management. Therefore, it is necessary to plan research precisely taking into account the balance of energy.

Most studies are based on the use of transmission ratios or production speed to determine the various results of the process associated with the category of waste [12]. These coefficients are mainly derived from the literature or taken from a specific situation. This means that often the results of the process are incorrectly related to their specific input properties and operating conditions. Therefore, when conducting such studies, there is a need to confirm the hypotheses put forward by the experiment.

Given all of the above, it is expected that the MFA-LCA waste integration model will have properties that would distinguish it from its counterparts. First, it will respond to changes in the fractional composition of waste, such as the ratio of organic matter, paper, metal, etc. Secondly, it should include the stage of substitution by energy systems and the production of primary resources. Also, be able to include in the calculation of energy consumption for a particular situation.

It can be concluded that the use of MFA-CLA in the field of waste management has many obstacles and that the dynamic MFA has never been applied to the modeling of the technological process of mechanical and biological processing enterprises (MBP). However, the presence of a significant number of publications in this area [13] confirms the effectiveness of this combination of methods. Therefore, its further application for the set tasks is justified.

Therefore, it is advisable to dwell on the review of the experience of applying the MFA directly. MFA has been widely used to evaluate the effectiveness of waste management scenarios to achieve environmental goals. Thus, with the help of MFA, waste in the ocean was estimated [14], a waste management system in megacities [15], large regions and even in countries [16].

MFA is an effective method for modeling in anaerobic digestion since it can be used to visualize the promising ability of raw materials to anaerobic biological decomposition, and empirical data for many fractions of waste are available in the literature [16].

MFA can be considered on two levels: the level of substances and the level of goods. Over the past decade, MFA has become extremely widespread. This method is used even in official EU statistical reports. MFA is used as a tool in a number of waste management studies, during the quantitative determination of waste and substance flows in waste. Combining it with waste life cycle (CLA) assessment will provide a deeper understanding of processes.

Life cycle assessment is one of the tools that makes it possible to comprehensively assess the ecological, economic, social aspects, and environmental impacts in the systems of production and waste disposal (Fig. 1).

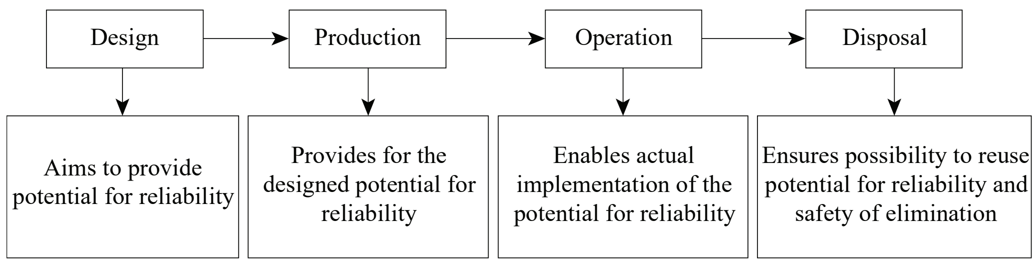

Fig. 1. Stages of the product life cycle

Material flow analysis (MFA) is a system analysis tool, the potential of which can solve complex problems. With the help of MFA, a systematic assessment of the flows and reserves of material in a system that is defined in space and time is carried out.

There are very few studies on the application of assessment models to the technological process of household waste disposal at mechanical and biological processing plants. However, from an economic point of view, the construction of these facilities, as one of the stages of the household waste management system, is the most rational solution. Therefore, studies of the technological process of operation of these facilities are necessary in order to increase their efficiency, especially the preservation of energy resources against the background of the upcoming fuel and energy crisis. This is justified by the fact that it is alternative energy that contributes to the stable and harmonious development of territories. However, until now, alternative sources are not well understood, the study of new promising areas of this type of energy is only at the initial level. Therefore, a responsible approach to assessing the advantages and disadvantages of methods is necessary. This is indicated by a number of studies, for example, the experience of using alternative fuels in aviation can potentially pose certain risks both for aviation technology and for the environment and the population [17, 18].

Anaerobic digestion of household waste at MBP enterprises is one of the most optimal technologies among the existing ones in the world. MBP technologies make it possible to conserve resources and in the next production cycle to obtain renewable natural biogas and digestate, which is rich in nutrients [19]. This, in turn, makes it possible to use the obtained substances in the future: biogas can be used for heating or heat and electricity production [20], and digestate should be used in the agricultural sector [21].

All this suggests that the issue of modeling anaerobic digestion is covered in scientific works. However, there is no comprehensive assessment of the application of material flow analysis and life cycle assessment. This is primarily due to the lack of information on the technological features of the work of MBP enterprises and its impact on a comprehensive assessment of the waste management system. Therefore, a detailed study of the issue of modeling changes in the properties of household waste during their pretreatment in the MBP technological process deserves a detailed study.

The search for an integrated waste management planning tool based on the integration of material flow analysis and life cycle assessment on the example of the work of a mechanical and biological processing plant necessitated research in this area.

3. The aim and objectives of the study

The aim of this study is to develop a model for improving waste management on the example of the process of anaerobic digestion of waste. The practical use of the results of the developed model will contribute to the adoption of effective, energy-saving strategic and investment decisions by the heads of waste disposal enterprises through their assessment. This will make it possible to avoid subjectivity when making decisions on the choice of waste management methods, will contribute to the selection of an effective and energy-saving method in future decision-making cycles.

To accomplish the aim, the following tasks have been set:

– to investigate the technological process of the waste treatment stage before anaerobic digestion and assess its impact on the biogas yield and the formation of digestate;

– to conduct simulation of the quantitative assessment of the mass balance of the waste management system in which the mechanical and biological treatment plant will operate;

– to propose a method of combined approach to the analysis of material flows and life cycle assessment for a comprehensive assessment of a complex solid waste system.

4. The study materials and methods

The object of the study is the process of pretreatment of waste before anaerobic digestion at the mechanical and biological processing enterprise, as an innovative solution that should contribute to the improvement of the solid waste management system at the stage of processing and disposal.

The working hypothesis of the study assumes that the combined structure of the analysis of material flows could be used to analyze the life cycle. At the same time, the preservation of elements and mass would be taken into account and combined with the level of technological detail. This is necessary to cover the consequences of technical choice for the introduction of new innovative solutions in the waste management system. To do this, there is a need to develop interrelated models in the structure of material flow analysis – a tool that represents a system with its flows and processes based on the law of conservation of mass and their integration into the life cycle assessment model.

This approach makes it possible to comprehensively assess the system, both from the material, technical, and energy side, and from the environmental impact. The goal is solved by developing nonlinear models that generate a production function based on the input data of the composition and properties.

The study used models for the technological process of anaerobic digestion of waste with their preliminary processing. They are based on the constituent equations and the need for energy, able to maintain the balance of mass at the levels of substances and components. The following stages were simulated: drum separation, hydropulper work, and anaerobic methane tank; the impact of these technological stages on the waste structure was evaluated. This stage is performed to assess the biogas yield from waste.

The verification stage is the anaerobic digestion experiment.

For the laboratory experiment, samples of samples of household waste were used, which were simulated according to the morphological composition. Household waste was prepared and pretreated using anaerobic digestion in a laboratory plant.

Characteristics of waste. The collected household waste was sorted into 6 different fractions. In order to obtain the density for each fraction of waste, mass and volume were measured. The elemental composition, humidity, and volatile solids for each of these fractions were determined based on [22].

Modeling the real process of the drum screen, the waste was sifted based on five particle size ranges (0.5–2 cm, 2–3 cm, 3–5 cm, and more than 5 cm).

Waste preparation. Different fractions of waste, which were previously characterized by particle size in the range of 0.5–5 cm, were mixed together for anaerobic digestion tests. Up to 95 % of the water content was added to the waste stream since 95 % of the mass filling the biogas generator should be water. In order to obtain pulp, the resulting mixture of waste and water was crushed. The light and heavy fractions were divided by density.

The process of anaerobic digestion of household waste. The process of anaerobic digestion of waste was simulated using 2 types of processes: structural and chemical, dividing them according to the work of the technological equipment on which they are recycled. Thus, processing on a drum screen, the work of a hydropulper and a process in an anaerobic methane tank were simulated.

The waste stream acts as input data for the model. Waste was divided into 6 categories. For these categories, the distribution of particles by size was determined. The work determines the type of distribution for untreated waste and for waste that has been crushed. Distribution parameters are calculated on the basis of experimental data.

5. Research results and development of a waste management planning tool

5. 1. The influence of the technological process of waste treatment on the biogas yield

5. 1. 1. Description of technological processes of waste pretreatment before anaerobic digestion

For the task set, the composition of waste is advisable to evaluate at three levels: by the flow of waste, by component composition, and by elemental composition. Such an assessment should be carried out to adequately predict the yield of biogas and digestate.

For three levels, property matrices are indicated. This matrix contains all the information necessary for calculations, such as the physical properties of waste, the kinetic constants of chemical reactions, and their geographical location. Thus, it is possible to represent all possible combinations of composition for a given waste stream: level 1 is flow (biogas and digestate); level 2 – component composition (separate fractions of waste); level 3 – elemental composition (pulp from waste).

The input data for the preprocessing model are mass flows of solid waste fractions. For modeling, it was assumed that the entire flow of the pulp formed from the waste enters a special stream of pulp-biofluid after further processing.

Ideally, biomass should be contained only in the flow of biofluids. However, 100 % efficiency is unrealistic since part of the biomass does not decompose, so losses from the potential are taken into account. This made it possible to take into account a realistic assessment of the potential for the reduction of pulp-biofluids, that is, the total amount that can be recovered.

The mathematical formulation consists of a mass balance. The mass balance involved breaking the total dry mass flow into biofluid and material flow and determining the substances in the material flow.

The input data are waste flow and biofluid flow.

The model is designed for 6 fractions of waste: metal; glass; plastic; paper and cardboard; other waste; organic fraction.

The composition of the biologically processed material was calculated on the basis of the input composition of the material using degradation coefficients and transmission coefficients. The use of coefficients in the model has made it possible to make it more realistic and accurate, avoiding the risk of an overly simplistic approach that can often produce the same results, regardless of aspects such as territorial reference. In addition, the simulation based on the composition of waste is useful for investigating the redirection of waste fractions to alternative treatment and for determining the origin of pollutants contained in the digestate.

The decomposition of organic material for each fraction of waste was determined experimentally based on the potential of methane in the case of anaerobic digestion. The degradation coefficient was determined for each fraction of waste undergoing biological treatment since the ability to decompose can vary significantly between them.

The model assumes that non-decaying fractions (i.e., glass and plastic) remain unchanged during biological treatment: their dry matter composition does not change, and they do not contribute to any emissions. The number and composition of fractions of the decomposing material vary during the process as they decompose and can cause emissions into different environments.

Transmission coefficients are mass-saving and, taking into account all outputs, are equal in total to units for each fraction of waste.

When developing the proposed modeling, the goal was set to create a common structure for the treatment of household waste, which would be as universal as possible.

Therefore, it is expedient to consider and evaluate the technical preparatory processes that occur before the aerobic transformation process for a deep understanding of what factors influence the yield of final products – biogas and digestate – when processed at MBP enterprises.

Based on the technological processes of processing that occurs during the preparation of fractions of household waste, these influences can be classified into two types: structural and chemical influences.

They are described as follows:

– type 1 – structural processes – technological influences that cause a change in the physical properties of waste but do not damage the molecular structure of waste components;

– type 2 – chemical processes – influences that cause a change in both the physical properties and the molecular composition of waste components.

The sequence of treatment is shown in Fig. 2.

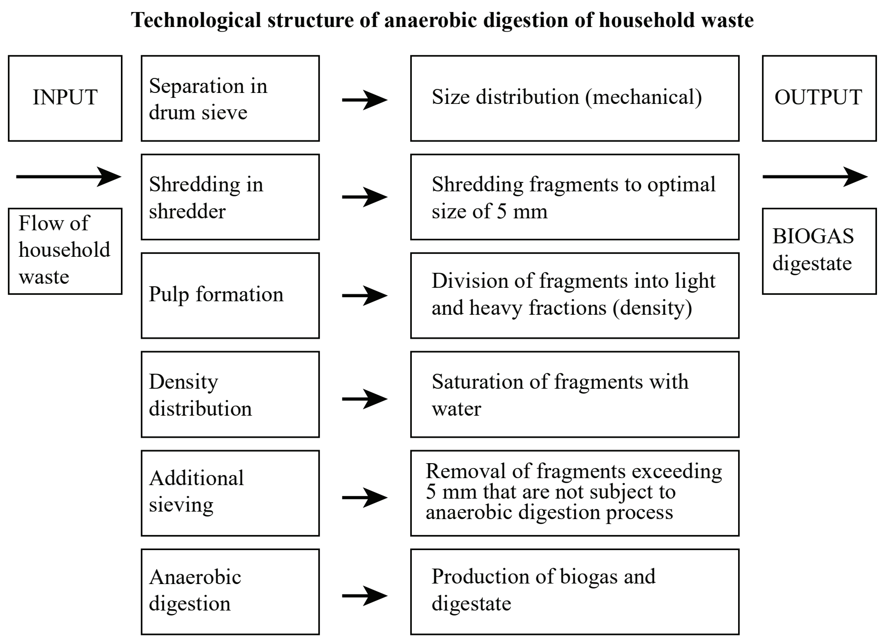

Fig. 2. Technological structure of anaerobic digestion of household waste

Separation in a drum sieve. At the first stage, the technological process of separation in the drum sieve should be evaluated.

The simulation is based on calculating the cumulative probability that a particle with a given size and physical properties passes through the holes of the drum.

Thus, the separation efficiency in the sieve of the drum directly depends on the size of the waste particles. Energy consumption in this case should be calculated on the basis of the total mass flow.

The process of operation of the hydropulper. The hydropulper was modeled as a sequence of three stages: grinding, density separation, and sifting.

When modeling the grinding stage, it is accepted that the grinding efficiency depends on the time the particles stay in the equipment. A classification and recycling stage was also added to the process to control the original particle size. Energy consumption has also been defined as a function of mass consumption and moisture content in waste.

Then, based on experimental results, the separation by density was simulated. During this stage, plastic and paper were collected by flotation, while glass, metals, and other organic matter not accepted for collection were deposited. Therefore, it has been accepted that all the previously listed components were completely separated during this stage, with the exception of fibers and other organic substances. In this case, a yield of 75 % was adopted on the basis of experimental observations that only a part of these fractions came into the resulting cellulose.

The sifting stage was modeled as a physical process of separating waste with a particle size of less than 0.5 mm from the rest. The 100 % effectiveness of this separation through a sieve is assumed.

5. 1. 2. Modeling of anaerobic digestion

To simulate the process of anaerobic digestion, the main microbiological reactions were identified. The conversion for these reactions has also been determined based on the hydrolysis rate, decaying waste fractions, and the volatile solids content in the waste.

The constants used for each component of the waste are taken from open sources of waste research conducted by the International Waste Working Group and the International Solid Waste Association [22] and given in Table 1.

Table 1

Properties of anaerobic digestion of various components of waste

Fraction	Percentage in total flow	Content of volatile solids, %	Reference hydrolysis constant	Non-hydrolyzed fraction of volatile substances
Paper and cardboard	14.2	89	0.054	0.454
Glass	12.9	0	0	1
Metal	1.18	0	0	1
Plastic	18.67	95	0	1
Organic waste	46.74	95	0.4	1.172
Other waste	6.31	3	0.021	0.172

For a specific study, a storage time of 30 days was used. The model is designed to work in continuous mode. Based on this, a non-hydrolyzed fraction of the waste component was calculated for each waste using equation (1):

$$S=\frac{S_0\left(1+\theta\kappa\beta\right)}{1+\theta\kappa}, \quad (1)$$

where S is the non-hydrolyzed fraction, S_0 is the total content of volatile solids, β is the non-hydrolyzed fraction of volatile solids, k is the hydrolysis constant, and θ is the retention time

The hydrolysis constant, k is an indicator of the difference by the reference hydrolysis constant calculated for the particle size of 5 mm, and the diameter of the particles received was taken according to data from [23], as expressed by equation (2):

$$k=\frac{6K_0}{\delta D}, \quad (2)$$

where D is the average diameter and δ is the density of the fraction. For each component of the waste stream, an average diameter was calculated, defined as the expected value of the probability density function of the particle diameter. This made it possible to calculate the hydrolysis constant for a given particle size distribution.

The composition of biogas includes the following components: the main part is methane, carbon dioxide, as well as small amounts of hydrogen sulfide, ammonia, etc.

Then it was possible to estimate the flow and composition of biogas, assuming a complete reaction, as expressed by equation (3):

$$C_aH_bC_cN_dS_e+\left(a-\frac{b}{4}-\frac{c}{2}-\frac{3d}{4}+\frac{e}{2}\right)H_2O\rightarrow \left(\frac{a}{2}-\frac{b}{8}-\frac{c}{4}-\frac{3d}{8}+\frac{e}{4}\right)CH_4+ +\left(\frac{a}{2}-\frac{b}{8}+\frac{c}{4}-\frac{3d}{8}+\frac{e}{4}\right)CO_2+dNH_3+eH_2S. \quad (3)$$

The digestate flow should be calculated with the assumption that the entire non-hydrolyzed fraction calculated earlier will fall into the digestate and that the entire hydrolyzed fraction that is not covered by equation 4 will also remain in the digestate.

Energy needs have been modeled on two approaches. First, the need is calculated based on the energy balance of the system. An enthalpy reaction of 58 kJ/kg, (4) [24] and a heat loss of 10 % were accepted:

$$C_6H_{12}O_6=3CH_4+3CO_2;\ \Delta\Pi=58\ \text{kJ/kg}. \quad (4)$$

In addition, based on known sources [23], it was assumed that the need for electricity for the process is 20 kWh/MWh of biogas production.

The energy balance of a biogas plant connected to a cogeneration unit for the production of electricity and heat is shown in Fig. 3.

It should be noted that most of the energy chemically bound in substrates will not have practical value. Chemically bound energy, which is not converted into biogas, is stored in solid and liquid residues, and has little potential for methane production.

About 40 % of energy can be converted into electricity and heat.

The energy flow diagram clearly indicates the different ways of "loss" of energy from the system. These energy flows should be the starting point for optimizing the process with the measures taken to increase biogas yield in order to reduce the potential for methane generation from waste.

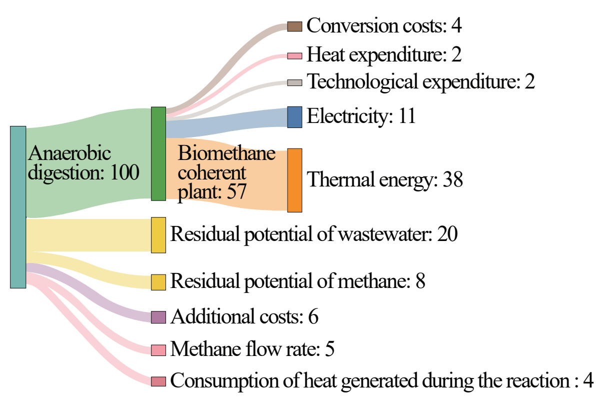

Fig. 3. Energy balance of anaerobic digestion process at the enterprise of mechanical and biological processing, % of flow yield

5. 1. 3. Verification of the anaerobic digestion process model by comparison with laboratory experiment data

It is worthwhile to dwell in more detail at the stage of modeling anaerobic digestion. The study developed a model to predict the yield of biogas and digestate by anaerobic digestion after a sequence of physical pretreatment of municipal solid waste. During these processing steps, the waste is subjected to anaerobic digestion.

In the study, an experiment was staged to simulate the conditions of the anaerobic digestion process. The material used in the study consists of a stream of different fractions of the solid waste fraction. Prototypes of the waste were sorted and crushed in a variety of ways, and then mixed several times in the laboratory. This process was intended to simulate the technology of primary treatment of waste in a drum screen, to study the impact of primary preparation for biogas release. The conditions of the experiment were maintained at room temperature of 25 °C. The resulting gas and digestate were evaluated to determine their composition and properties. The chemical composition of materials was analyzed using standard methods of analysis.

The experiments were carried out on a laboratory mini-reactor with a total capacity of 2 liters (Fig. 4).

The reactor was made of borosilicate glass with a sampler. The bottles were covered with rubber plugs equipped with tubes to remove gases and adjust the pH. The effective volume of the reactor was maintained at 1.6 liters. The volume of water displaced from the bottle was equivalent to the volume of gas formed. The reactor was stirred by hand by shaking and stirring once a day. The reactors operated at room temperature to correctly simulate the working conditions of the mechanical and biological waste treatment enterprise.

Gas production was measured at a fixed time daily using the water displacement method. All gas volumes were measured at an average temperature of 25 °C. Substrate was mixed once a day when gas was measured. Gas samples were taken by gas injectors for sampling. The composition of biogas (CH_4+CO_2) was determined using a gas chromatograph.

The yield of biogas and digestate was calculated on the basis of input properties and composition. Thus, the methodology allows us to vary the properties and composition of waste when handling them in order to obtain higher rates of biogas yield.

The model demonstrates that during the technological processing of household waste, the concentration of contaminants (for example, the copper content) is significantly reduced, as shown in Fig. 5.

Fig. 7 shows that the model can estimate the change in several critical parameters for subsequent processes in the processing sequence and can be very useful for choosing the most suitable processing method.

The model makes it possible to predict the amount of biogas and digestate produced. Thus, according to the simulation results, a biogas yield of 315 l/kg was predicted while during the experiment an output of 350 l/kg was obtained (Table 2). These indicators indicate the adequacy of the model since the error is 10 %, which is a good predicted value.

The difference between the yield of CH_4, obtained experimentally and using the model can be explained by the difference in parameters, such as particle size. Therefore, the goal was further set to experimentally assess the potential yield of methane, which can be obtained with greater grinding of waste fractions.

Fig. 6 shows that a decrease in the diameter of waste particles tends to increase the yield, as expected.

Table 2

Comparison of biogas yield between experimental data and model forecasts

Characteristic	Experimental data	The predicted value of the model	Deviation
Biogas yield	350	315	–10 %
	330		–5 %
	345		–9 %
Percentage of methane	58	53	–9 %
	62		–15 %
	50		6 %

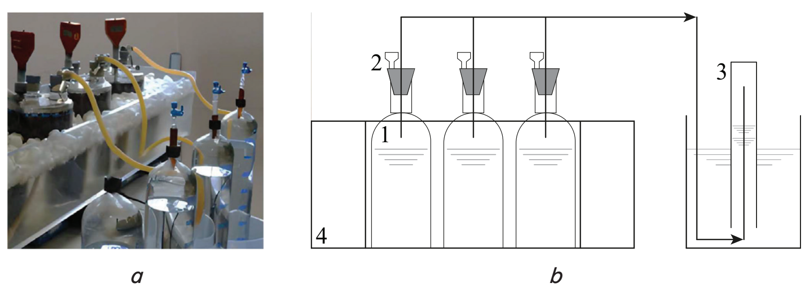

Fig. 4. Laboratory mini-reactor: *a* – photograph; *b* – scheme: 1 – reactor; 2 – pH-meter; 3 – gasometer for measuring methane; 4 – water bath

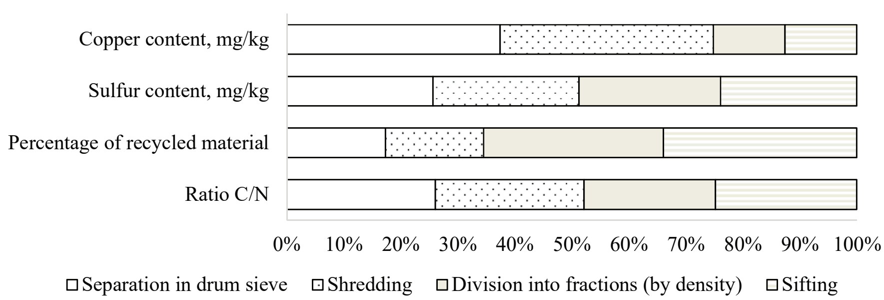

Fig. 5. Change in parameters during the sequence of the waste treatment process: copper content, mg/kg; sulfur content, mg/kg; percentage of decomposing material, kg/kg of total dry weight; C/N ratio

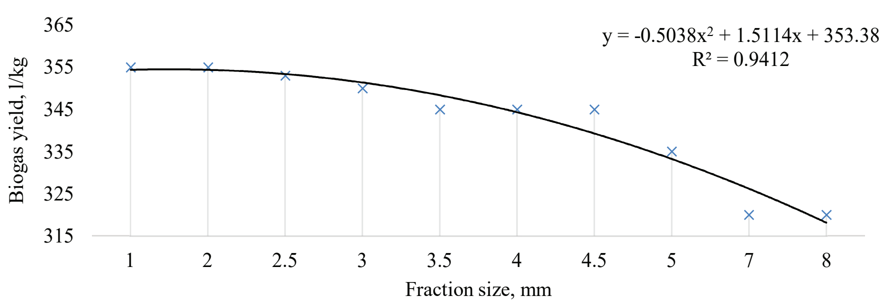

Fig. 6. Dependence of biogas production on grinding intensity

Therefore, our results indicate the relationship between the change in the physical properties of waste fractions that occur with the waste flow during its processing before the anaerobic digestion process with the percentage of biogas and digestate production.

5. 2. Computer simulation of material and energy balances of the functioning of a plant of mechanical-biological processing

MFA modeling was performed using STAN2web software. The application of STAN made it possible to visualize the MFA system, perform data reconciliation, and take into account the uncertainty of the data.

The choice of software was dictated by the fact that it has proven successful in assessing the waste management system in such studies [25].

The boundaries of the system extend from the place of primary collection to the final disposal. The following scenario was considered: Waste treatment at the mechanical and biological processing plant with the production of biogas and digestate with partial combustion and disposal of ash at an HSW landfill.

The technological process of the plant of mechanical and biological treatment of waste can be simulated using mass and energy balances.

Process description: a unit with single-stage anaerobic digestion for the treatment of household waste and the production of biogas, which is then generated into electricity and heat, and digestate used as fertilizer. Initial hydrolysis and acidification occur in the same reactor as methane production. The wet process has a humidity of more than 95 %. The main technological processes are energy consumption for heating the reactor to thermophilic temperature, diesel for the operation of equipment at the plant and electricity for pumps, mixers, etc.

The parameters are selected on the basis of measurement data from a number of European biogas plants [26]. It was decided not to evaluate a particular plant since none can provide data for all the parameters necessary for modeling the process and, thus, a hypothetical installation for anaerobic digestion was represented.

In the resulting fractional composition of the waste stream, more than half of the dry matter (56 %) can potentially be restored to the flow of biofluids from the pulp of fractions of organic matter, paper-cardboard, and other residual stuff (Fig. 5).

5.9 Gj of primary energy can be obtained from this pulp-bioliquid, of which 70 % can be transferred to methane (4.1 Gj) based on a yield of 68 % relative to the measured potential of methane and digestate (1.8 Gj).

From the specified biogas, you can get 460 kWh (±80) of electricity and 2060 (±360) MJ of heat.

Material and energy flows are graphically represented in Fig. 7. Abbreviations in Fig. 7: M – metal; C – glass; P – plastic; PC – paper and cardboard; I: other waste; O – organic fraction; BP – bioridna-pulp; A – ash; CD – carbon dioxide; BG – biogas; DG – digestate.

The uncertainties associated with the corresponding flows are specified as standard deviations of averages.

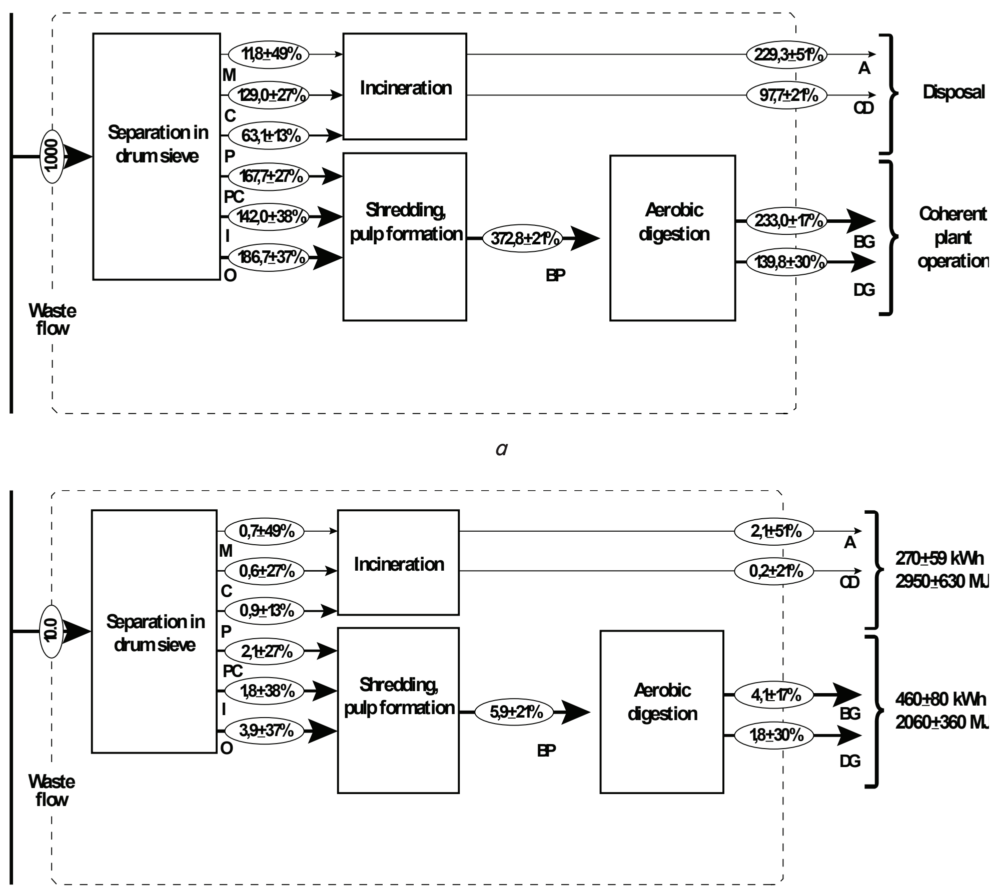

Fig. 7. Model of mass energy flows at an enterprise of mechanical-biological processing: *a* – mass flow; *b* – energy flow

The contribution of enzymes to the total mass flow was approximately 0.4 %, that is, insignificant compared to the total flow of waste, and therefore was not taken into account separately.

5. 3. Combined approach to material flow analysis and life cycle estimation

The waste management system can be described by models that have a more detailed representation of various processes. They would also have the ability to record the impact of operating conditions and input flow characteristics. This is done by developing models based on basic equations (mass and energy balances, reaction kinetics, transfer phenomena) for each process in order to evaluate their output as a function of the actual elemental composition and operating conditions of the process.

The study uses an approach that combines two systemic methodologies: material flow analysis and life cycle assessment. This makes it possible to quantify the waste management system and use scenario analysis to assess the potential effectiveness of various management policy measures.

The fact is that it is extremely difficult to predict all emissions for a specific scenario of a waste management system based only on reaction equations. Therefore, this section presents an alternative way to estimate all specific emissions that are not yet covered by the equations. A procedure for coordinating data to fill in the initial values that are not yet provided for by the model is proposed. The model makes it possible to include additional information and additional flows from LCA stocks. Then the resulting description of the process is rebalanced to ensure the safety of all elements. This aims to minimize differences relative to the initial description of the process.

The basic principle of the method can be formulated as follows: materials cannot be lost, which implies the preservation of matter and energy. Therefore, the total mass of inputs should be equal to the volume of outputs and system stocks. Technically, this can be illustrated using equation (5):

$$\sum_{k_i} m(input) = \sum_{k_0} m(output) + m(stock), \qquad (5)$$

where k_i and k_o represent the input and output flows, respectively, and m represents the material flux [27].

It is proposed to use a combination of methodologies to quantify the environmental efficiency of the waste management system with disposal at the mechanical and biological treatment plant.

Analysis of the material flow can be useful in assessing options that can later be evaluated according to the methodology for assessing the life cycle. For this reason, the current study proposes a methodology in which MFA and LCA are integrated into a continuous cycle of selection of methods, providing feedback and continuous improvement (Fig. 8).

The integration of two methods – analysis of the material flow and assessment of the life cycle in the cyclical system of selection of methods for solid waste management – makes it possible to increase the efficiency of the waste management system, primarily in the issue of energy saving.

Evaluation of life cycle options is carried out after analyzing material flows. This makes it possible in the future to provide for the assessment of the life cycle only those options that provide optimal benefits. The peculiarity of the proposed solution is to reduce the time for the selection of the optimal scheme of handling and the introduction of methods for handling solid waste.

Thus, at the first technological and economic stage, with the help of MFA, methods of solid waste management are selected, which contribute to the reduction of material and energy costs. At the second, so-called environmental stage, by assessing the life cycle, the impact of the selected waste management system on the environment is assessed.

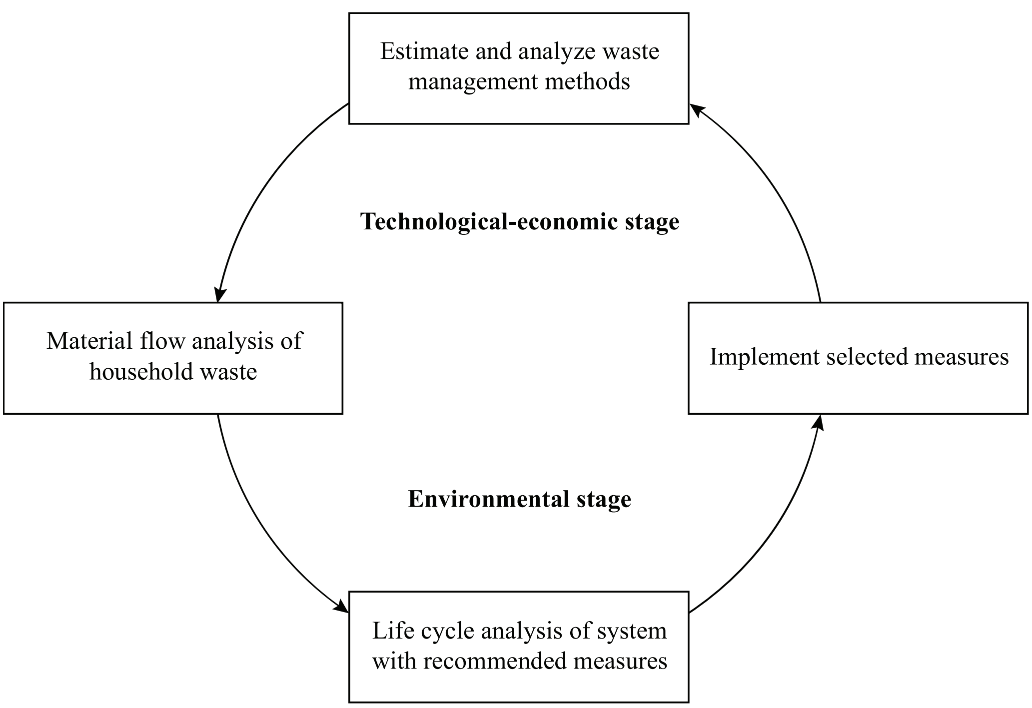

Fig. 8. Tools for evaluating waste management methods, combining material flow analysis and life cycle assessment

Similarly, the implementation of new decisions and measures taken on the basis of the LCA carried out provides feedback data that should be used in future material flow analysis.

On the one hand, MFA is a tool for evaluating the effectiveness of a waste management system but using only it is impossible to make informed decisions about waste management. On the other hand, the LCA does not always guarantee that the best alternatives will be chosen, especially if other economic factors reflecting the special interests of the inhabitants of the settlements are taken into account. Therefore, it is advisable to decide on the integration of two analyzes to select effective methods of waste management.

First, an MFA analysis should be carried out and then the results presented should be interpreted. At this stage, the performance of the waste management system is evaluated by a set of selected indicators. Next, separate scenarios should be developed, each of which represents a set of specific measures or technological operations aimed at improving the system of solid waste management. These scenarios are evaluated using the same indicators by which the existing system of solid waste management was evaluated. This step represents a stage of evaluation and analysis of options and is necessary to assess the degree to which each set of interventions will improve the existing system of solid waste management before the life cycle assessment is started. This ensures that during the life cycle assessment, only those options that will lead to significant improvements in the solid waste management system will be considered. At the next stage, an assessment of the LCA life cycle should be performed, on which it is advisable to carry out an assessment according to the criteria of environmental impact.

Ultimately, the best scenario of action is selected and implemented. This provides feedback data for consideration in future material flow analysis. In the following sections, this approach is illustrated with a single example without selecting the best option.

Combining flow analysis with environmental assessment seems like an attractive tool for comparing alternative technologies. It will be useful for supporting waste management decisions at both the strategic and operational levels. The method of analysis of material flows applied in the work can be used to optimize the effectiveness of the system and provide reference information for further analysis of the life cycle assessment.

6. Discussion of results of modeling the technological process of the waste treatment stage before anaerobic digestion

The method of evaluating the implementation of an innovative solution, which involves the integration of two systemic methodologies: analysis of material flows and assessment of the life cycle, is highlighted. The integrated method provides for the possibility of quantifying the waste management system and using scenario analysis to assess the potential effectiveness of various waste management policy measures (Fig. 8). This is done by developing models based on the basic equations: mass and energy balance (Fig. 7), reaction kinetics, and transfer coefficients for each process to evaluate their output as a function of the actual elemental composition and working conditions of the process. The simulation result was carried out on the example of waste treatment at an enterprise of mechanical-biological treatment (Fig. 7).

The model developed in the paper is used to predict the production of biogas by anaerobic digestion after the sequence of physical pretreatment of household solid waste (Fig. 5).

The mathematical description of the process is based on the equation of the flow reaction and the composition of biogas (3) and the equation of enthalpy of the reaction (4).

The sequence of processing (Fig. 2) from the first mechanical sorting of particles by size to anerobe fermentation. It was modeled on the basis of a methodology explained for two types of processes: structural and chemical, depending on the technological processes of processing, which cause a change in the properties of waste components. Drum separation, hydropulper, and anaerobic methane were introduced. During these stages, the waste is cleaned: contaminated fractions and other substances are separated to facilitate their future anaerobic digestion. The output of each equipment is calculated on the basis of input properties and waste composition. Thus, the methodology makes it possible to vary the properties and composition of waste throughout the pretreatment stage.

To simulate the process of anaerobic digestion, the main microbiological reactions were identified. The conversions for these reactions are determined based on the rate of hydrolysis, the decomposing waste fractions, and the content of volatile solids in the waste according to formulas (1), (2). The constants used for each component of the waste are given in Table 1.

The performed simulation of the anaerobic digestion process indicates that the processing sequence makes it possible to reduce the C/N ratio and increase the content of decomposing waste. It is these two parameters that are extremely important for obtaining the yield of methane during anaerobic digestion.

However, the results also show that even if some properties of the waste are improved for further anaerobic digestion, some of them have the opposite effect, for example, the sulfur content (Fig. 5). In this case, an increase in its concentration can be observed. Here it is necessary to take into account the weight coefficients of biogas yield, depending on the sulfur content. Since a decrease in sulfur content by 3.96 % is not a relevant factor of influence, the technological stage of distribution into fractions by density should be left. Especially considering the fact that the stage increases the percentage of processed material and the C/N ratio by more than 7.55 % and by 7.34 %, and the weight effect exceeds 1.5 and 2.7 times, respectively.

The obtained results of the laboratory experiment demonstrate that there is a clear relationship between the change in the physical properties of waste fractions occurring at a certain stage of the process of their processing, with the process of anaerobic digestion (Fig. 6). In addition, the data provide information on the need to purchase crushing and threshing equipment with a cutting capability of 2 mm. It should also be noted that the experiment showed the inexpediency of selecting equipment with a greater cutting capability since it cannot fundamentally increase the yield of methane but the energy consumption of such equipment is almost three times higher.

Regarding the modeling of mass and energy flows (Fig. 7, *a*, *b*), in general, the results showed that approximately 80 % of the mass of the flow of solid waste can potentially be restored in the flow of pulp-biofluids with anaerobic digestion at MBP enterprises.

However, 11–19 % of the total biomass intake (i.e., organic waste, paper, cardboard, etc.) were found in the flow of solids (mainly in residues). This is the lost potential of biomass: it is not partially liquefied and, therefore, cannot be restored like a biofluid. However, biomass can be further reduced by improved enzymatic processing in order to optimize the overall decomposition of biomass and facilitate further separation from the remaining solid fractions. This is possible by adjusting the retention time and reducing the particles that are subjected to fermentation.

In this respect, the role of purification will be fundamental to maximize the separation of biofluids and solid parts and thus is promising until the bioenergy is fully restored.

In general, the integration of the recovery of materials, bioenergy (from biofluid-pulp) and energy (from residual solids) can make the performance of this technology equal to or higher compared to expensive waste disposal technologies.

The study can be applied in the assessment of measures for the need to introduce innovations of anaerobic digestion – the construction of plants or installations in the waste management scheme. However, for its use, it is necessary to know the morphological composition of the waste, including its seasonal fluctuations.

Our study has certain limitations. In real conditions, the efficiency of operation of waste management facilities (including the enterprise of mechanical and biological treatment, which is considered as an example in the study), depends on the quality of incoming raw materials. Therefore, it is extremely important when assessing the energy potential to verify data on the morphological composition of waste throughout the year. The approach developed in the study should be considered as a basic one that needs to be clarified under real conditions of implementation.

The disadvantage of the study is the failure to take into account the actual data on the economic indicators of the project for the introduction of the waste pretreatment process at the mechanical and biological processing enterprise. The introduction of innovation requires significant investments, and therefore it is correct to take into account not only the material, energy, and environmental aspects but also the cost.

The development of the study will consist in the development of qualitative criteria for assessing the life cycle for anaerobic digestion.

It is also planned to perform an assessment of an integrated and interconnected system consisting of a number of waste transportation and management processes with the help of MFA-CLA, ranging from primary collection to final disposal.

7. Conclusions

1. The developed model for forecasting biogas production by anaerobic digestion after pretreatment of municipal solid waste made it possible to take into account the input properties and composition of the waste stream. In the paper, the calculation is given for 6 fractions of waste: paper and cardboard (14.2 %), glass (12.9 %), metal (1.18 %), plastic (18.67 %), organic waste (46.74 %), other waste (6.31 %), as the most typical morphological composition.

The tool designed makes it possible to vary the properties and composition of waste throughout the entire processing sequence. The simulation also indicates that the sequence of processing steps makes it possible to reduce the ratio of carbon and nitrogen and increase the content of decomposing waste, which are two important parameters for obtaining a good yield of methane during anaerobic digestion.

The model also makes it possible to predict the amount of biogas produced. In addition, it is possible to predict its composition, primarily the percentage of methane in biogas. The biogas yield at the level of 315 l/kg was predicted by the model, while during the experiment an output of 350 l/kg was obtained. The calculated methane content was very consistent with the experimental one.

The method makes it possible to overcome the uncertainty associated with the subsequent application of the method of assessing the life cycle due to a better understanding of the different composition of the waste stream. Thus, such a structure can be used for a consistent analysis of the life cycle, which will take into account the factor of conservation of material resources and energy. This makes it possible to simulate changes in the properties of waste in a certain sequence of their processing: separation, grinding, separation by density, sifting to clarify the understanding of technological processes and provide reliable information for further optimization.

2. Computer simulation of the quantitative assessment of the mass balance of the waste management system in which the mechanical and biological treatment plant will operate was carried out to demonstrate the results obtained. We compiled material and energy flows. According to the obtained modeling, an MBP enterprise can recover about 56 % of the original dry matter in the form of a bioliquid, which potentially makes it possible to obtain 4.1 Gj of biogas energy from 1 solid waste, which corresponds to 460 kWh of electricity and 2060 MJ of heat. Other solid fractions that cannot be subjected to anaerobic digestion contained about 2.3 MJ, which were predictably subjected to heat treatment. The reduction of metals and plastic can provide additional environmental benefits. Possible scenarios for comparison could be alternatives such as burning, disposal, or use in brick kilns. However, in the study, only one scenario was chosen to demonstrate the method – incineration, as the most technologically possible. Future research will be aimed at increasing the level of detail of the model's forecasts, matching these results with the life cycle assessment. It is planned to add an inhibition equation to the anaerobic digestion model to represent a wider range of possible operating conditions and to refine the calculation of energy consumption for different processes.

3. The proposed method, which involves combining into a cyclical process the methods of analyzing the material flow and assessing the life cycle in order to make effective, energy-saving decisions, provides feedback and continuous improvement of the system. The practical use of the results of the developed model allows us to evaluate and select effective, energy-saving methods of handling. The proposed solution makes it possible to overcome the factor of subjectivity when choosing the elements of the waste management system.

The study showed that such integration simplifies the selection and evaluation of measures to improve the handling system. The integration of methods allows us to take into account in the process of selecting measures environmental factors of influence that have not been assessed through the MFA. The combination of MFA and CLA promotes the choice of alternatives in a transparent, repetitive, and less subjective way than the traditional decision-making method, which also provides an opportunity for improvement in future decision-making cycles. The study demonstrates the power of integrating MFA and CLA to improve waste management decision-making. For future research, it is planned to coordinate the results of the material and energy flows of the mechanical and biological processing enterprise with OLC. Calculations of energy consumption for various processes with changes in morphological composition also need clarification.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

References

1. Boichenko, S. V., Ivanchenko, O. V., Iakovlieva, A. V. (2017). Recycling and utilization of aviation engineering: the global trends and peculiarities of introduction. Science-Based Technologies, 2 (34). doi: https://doi.org/10.18372/2310-5461.34.11612
2. Boichenko, S. V., Leida, K., Ivanchenko, O. V. (2016). Ecologistics, utilization and recycling of vehicles: trends and prospects. Science-Based Technologies, 2 (30). doi: https://doi.org/10.18372/2310-5461.30.10568
3. Boichenko, M. S., Vovk, O. O., Boichenko, S. V., Shamanskyi, S. I. (2018). Perspectives of membrane bioreactors for wastewater purification from waste of pharmaceutical products and biogenic elements. Energy Technologies & Resource Saving, 3, 31–40. doi: https://doi.org/10.33070/etars.3.2018.04
4. Pavliukh, L., Shamanskyi, S., Boichenko, S., Jaworski, A. (2020). Evaluation of the potential of commercial use of microalgae in the world and in Ukraine. Aircraft Engineering and Aerospace Technology, 93 (3), 429–436. doi: https://doi.org/10.1108/aeat-08-2020-0181
5. Erses Yay, A. S. (2015). Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. Journal of Cleaner Production, 94, 284–293. doi: https://doi.org/10.1016/j.jclepro.2015.01.089
6. Kryvda, O., Tulchynska, S., Smerichevskyi, S., Lagodiienko, N., Marych, M., Naghiyeva, A. (2022). Harmony of Ecological Development in the Conditions of the Circular Economy Formation. Environment and Ecology Research, 10 (1), 11–20. doi: https://doi.org/10.13189/eer.2022.100102
7. Andersen, J. K., Boldrin, A., Christensen, T. H., Scheutz, C. (2011). Mass balances and life cycle inventory of home composting of organic waste. Waste Management, 31 (9-10), 1934–1942. doi: https://doi.org/10.1016/j.wasman.2011.05.004
8. Clavreul, J., Baumeister, H., Christensen, T. H., Damgaard, A. (2014). An environmental assessment system for environmental technologies. Environmental Modelling & Software, 60, 18–30. doi: https://doi.org/10.1016/j.envsoft.2014.06.007
9. Jensen, M. B., Møller, J., Scheutz, C. (2017). Assessment of a combined dry anaerobic digestion and post-composting treatment facility for source-separated organic household waste, using material and substance flow analysis and life cycle inventory. Waste Management, 66, 23–35. doi: https://doi.org/10.1016/j.wasman.2017.03.029
10. Zhang, H., Matsuto, T. (2010). Mass and element balance in food waste composting facilities. Waste Management, 30 (8-9), 1477–1485. doi: https://doi.org/10.1016/j.wasman.2010.02.029
11. Gentil, E. C., Damgaard, A., Hauschild, M., Finnveden, G., Eriksson, O., Thorneloe, S. et al. (2010). Models for waste life cycle assessment: Review of technical assumptions. Waste Management, 30 (12), 2636–2648. doi: https://doi.org/10.1016/j.wasman.2010.06.004
12. Laurent, A., Janoušek, V., Magna, T., Schulmann, K., Míková, J. (2014). Petrogenesis and geochronology of a post-orogenic calc-alkaline magmatic association: the Žulová Pluton, Bohemian Massif. Journal of Geosciences, 59 (4), 415–440. doi: https://doi.org/10.3190/jgeosci.176
13. Viau, S., Majeau-Bettez, G., Spreutels, L., Legros, R., Margni, M., Samson, R. (2020). Substitution modelling in life cycle assessment of municipal solid waste management. Waste Management, 102, 795–803. doi: https://doi.org/10.1016/j.wasman.2019.11.042
14. Bai, M., Li, D. (2020). Quantity of plastic waste input into the ocean from China based on a material flow analysis model. Anthropocene Coasts, 3 (1), 1–5. doi: https://doi.org/10.1139/anc-2018-0028
15. Hendriks, C., Obernosterer, R., Müller, D., Kytzia, S., Baccini, P., Brunner, P. H. (2000). Material Flow Analysis: A tool to support environmental policy decision making. Case-studies on the city of Vienna and the Swiss lowlands. Local Environment, 5 (3), 311–328. doi: https://doi.org/10.1080/13549830050134257
16. Vuković, J., Marčeta, U., Vujić, B. (2021). Identification of the causes of low recycling rate of paper in Serbia and assessment of current quantities using MFA. Acta Technica Corviniensis - Bulletin of Engineering Hunedoara, 14 (2), 17–20. Available at: https://acta.fih.upt.ro/pdf/2021-2/ACTA-2021-2-02.pdf
17. Boychenko, S. V., Matveeva, E. L. (1999). Monitoring antropologicheskoy deyatel'nosti v sfere ispol'zovaniya neftyanykh istochnikov energii. Ekotekhnologii i resursosberezhenie, 5, 54–57.

18. Boichenko, S. V., Khrutba, V. O., Yakovlieva, A. V., Antropchenko, A. K. (2016). Identyfikatsiya ryzykiv, shcho vynykaiut pid chas vykorystannia tradytsiynykh i alternatyvnykh aviatsiynykh palyv: Ekolohichnyi ryzyk. Naukoiemni tekhnolohiyi, 1 (29), 116–122. Available at: https://er.nau.edu.ua/bitstream/NAU/22088/1/10104-26171-1-SM.pdf
19. Harirchi, S., Wainaina, S., Sar, T., Nojoumi, S. A., Parchami, M., Parchami, M. et al. (2022). Microbiological insights into anaerobic digestion for biogas, hydrogen or volatile fatty acids (VFAs): a review. Bioengineered, 13 (3), 6521–6557. doi: https://doi.org/10.1080/21655979.2022.2035986
20. Szarka, N., Scholwin, F., Trommler, M., Fabian Jacobi, H., Eichhorn, M., Ortwein, A., Thr n, D. (2013). A novel role for bioenergy: A flexible, demand-oriented power supply. Energy, 61, 18–26. doi: https://doi.org/10.1016/j.energy.2012.12.053
21. Bernstad, A., la Cour Jansen, J. (2012). Separate collection of household food waste for anaerobic degradation – Comparison of different techniques from a systems perspective. Waste Management, 32 (5), 806–815. doi: https://doi.org/10.1016/j.wasman.2012.01.008
22. Lagerkvist, A., Ecke, H., Christensen, T. H. (2010). Waste Characterization: Approaches and Methods. Solid Waste Technology & Management, 61–84. doi: https://doi.org/10.1002/9780470666883.ch5
23. Esposito, M., Cannizzaro, G., Bozzoli, P., Consolo, U., Felice, P., Ferri, V. et al. (2008). Efficacy of prophylactic antibiotics for dental implants: A multicentre placebo-controlled randomised clinical trial. Eur. J. Oral. Implantol., 1 (1), 23–31.
24. Schmidt, T., Pröter, J., Scholwin, F., Nelles, M. (2013). Anaerobic digestion of grain stillage at high organic loading rates in three different reactor systems. Biomass and Bioenergy, 55, 285–290. doi: https://doi.org/10.1016/j.biombioe.2013.02.010
25. Arena, U., Di Gregorio, F. (2014). A waste management planning based on substance flow analysis. Resources, Conservation and Recycling, 85, 54–66. doi: https://doi.org/10.1016/j.resconrec.2013.05.008
26. Robinson, H., Robinson, T. (2021). Leachate treatment. Sardinia. Available at: https://www.sardiniasymposium.it/en/academy-leachate-treatment
27. Makarichi, L., Techato, K., Jutidamrongphan, W. (2018). Material flow analysis as a support tool for multi-criteria analysis in solid waste management decision-making. Resources, Conservation and Recycling, 139, 351–365. doi: https://doi.org/10.1016/j.resconrec.2018.07.024