KAUNAS UNIVERSITY OF TECHNOLOGY
VYTAUTAS MAGNUS UNIVERSITY
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EDGARAS STUNŽĖNAS

APPLICATION OF INDUSTRIAL ECOLOGY METHODS FOR FOOD WASTE MANAGEMENT ON A REGIONAL LEVEL

Summary of Doctoral Dissertation
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INTRODUCTION

Relevance of the research

Food waste (FW) and food wastage are problems, which cannot leave global organizations' agendas due to the environmental impact that they generate as well as the risks such problems pose to the future food supply. The scale of the food waste problem is not diminishing, and the demand for food grows along with the population, resulting in the tension in the entire supply chain and the waste management system. It is worth noting that the scale of food waste growth is not reduced by the economic development of countries, and it is still not possible to decouple the generation of food waste from the economic growth. A recently conducted research by the European Union institutions suggests using a broader definition of food waste, which includes inedible parts of food and encompasses the whole food supply chain. In this case, the problem of food waste becomes even more pronounced, as the boundaries of the system expand. Finally, the true extent of the problem is revealed by analyzing it from a holistic perspective. Taking into account natural and technosphere resources, labor force, emissions, wastewater, and soils destroyed by the intensive farming, the problem results in significant environmental impact and jeopardized food security in the future. The failure in ecosystem services, which are accountable for food production, would firstly result in food deprivation for the most vulnerable groups and ultimately, even a threat of war due to the dwindling resources. To summarize, food waste negatively affects all three components of sustainable development, and since the issue is a complex one, its solution requires the involvement of different disciplines to manage the situation.

From the perspective of food waste management, the scale of the problem does not seem to be significant, because nowadays, the world has sufficient waste treatment capacity. Nevertheless, the abundance of scientific articles in the field of key food waste management technologies reveals that these processes are not well managed and have a range of optimization opportunities. Various solutions can be applied to control the contamination of waste by heavy metals and pathogens, optimization options to recover more energy, techniques to reduce nitrogen emissions, phosphate, ammonia, nitrate losses, measures to increase the value of compost in terms of nitrogen, phosphorus, potassium, and organic matter. Conventional waste management methods can be optimized by increasing their speed, decomposition efficiency, odor release, etc. An extensive database of scientific articles is constantly being supplemented by research that analyzes the optimization of energy production from biomass, thus using the solar energy that is stored in bio-materials. Another broad group of scientific articles is exploring the possibility of producing value-added products from by-products that are generated during the supply of both plant and animal products. Although the most value-added products appear to be quite complex and their production is investment-intensive, value-added can be created simply by using the by-products of production to produce feed, fodder, and even food.

In addition to traditional "end-of-pipe" technologies, a relatively large number of preventive measures can be found in the practical literature, which help to "save" the food. These include a variety of apps that allow full consumption or sharing of food, refrigerator cameras to monitor and plan cooking, ethylene adsorbers, various sensors, initiatives to promote unconditional products, artificial food waste prevention systems, and software to control stocks of food, etc. All preventive measures and technological solutions that allow food to be returned to the supply chain contribute to the reduction of intensive agriculture and, consequently, environmental impact.

The aim of this doctoral dissertation is to propose a model that would allow the integration of the above-mentioned solutions in various regions based on the concept of industrial ecology. A region is considered in this work as a unit of a certain geographical territory (or the whole territory of the State) of the State in question, which is united by certain features related to the management of municipal waste. For example, Lithuania has a regional municipal waste management system (10 Regional Waste Management Centers (RATC)), i.e., each municipality of Lithuania has a system based on the waste management plan for the region.

Aim and objectives of the research

The aim of the work is to create a decision support model for food waste management based on the industrial ecology concept.

The objectives of the research are as follows:

- To carry out an analysis of the scientific and practical literature as well as applicable environmental and other legislation in the field of food waste streams, their properties and management methods, systems, and models;
- To conduct theoretical and practical research on the application of industrial ecology elements for food waste management in order to set guidelines for the model development;
- To offer a model of integrated food waste management for food waste management at the regional level, based on the concept of industrial ecology;
- To approbate the proposed model for significant food waste streams that were selected for a chosen region.

Statements for the defence

- Food waste must be analyzed throughout the life cycle of the food, and the system boundaries must be extended to a region.
- For food waste management at a regional level, a decision support model, in which the elements of industrial ecology are integrated, is proposed. The application of this model would allow an optimal use of the material (nutritional) and/or energy properties of food waste with minimal impact on the environment.

Object of the research

The object of research is food waste and its management system.

Methodology

The decision support model and its application algorithm were developed based on the theoretical and practical research and approval results (analyzing the selected region). Firstly, based on the theoretical research, a prototype of the model was created, which was finally refined and adjusted based on the results of the practical research and approval. The development of the model application algorithm was based on the assumption that its initial structure is based on the comparison of existing and alternative food waste management systems.

The theoretical research has been conducted while analyzing the scientific and practical literature on the food waste management solutions that are in line with the concept of industrial ecology and its elements (dematerialization, industrial metabolism, interactions with the biosphere, restructuring of energy systems, policy making, development of industrial ecosystems (ecological parks)). The accumulated sources that matched the search criteria were divided into 5 groups. A further investigation was made on how to integrate and combine the food waste management measures that were set out in these 5 groups in order to realize the concept of industrial ecology in regional food waste management.

The practical research in the development of the model and its application algorithm emerges with the aim to generate an additional source of information based on a practical attempt to implement management alternatives based on the concept of industrial ecology in the selected region. The added value of such research is the consideration of factors that are rarely taken into account in the scientific literature, which include legal regulation. The practical research allows delving into the implementation steps of alternatives, the information and methods that are required; this is exactly the data that is needed to develop an application algorithm. The practical studies have been selected that the obtained data could be used in the approbation of the model.

Scientific novelty of the research

The proposed model for the integrated food waste management greatly extends the scope of this waste management system. In particular, the extension of the boundaries is due to the regional approach for food waste management; therefore, one of the reasons is simply the area in question. Although a regional approach to waste management is mandatory for the EU Member States (regional and national waste management plans are being developed and implemented), food waste is only included as a part of the municipal waste stream, which is the only stream focused on this work. Another aspect that extends the boundaries of the system is the application of a broader definition of the food waste compared to the conventional one that dominates in the scientific literature. The boundaries of the conventional food waste definition system are usually only food waste from the households and the catering sector.

The scientific novelty of the work is the application of industrial ecology to the biogenic waste stream, such as food waste, which is not limited to the application of only sole industrial symbiosis element but also widespread use of dematerialization with references to the remaining elements of industrial ecology (e.g., interaction with the biosphere, creation of eco-industrial parks, or restructuring of energy systems). This application stands out because most of the published scientific articles apply the concept of industrial ecology to the heavy industry and emphasize the creation of eco-industrial parks.

A strong distinctiveness of the work is the application of the industrial symbiosis element in a broader perspective than the conventional one. In the traditional case, the industrial symbiosis element is implemented when the waste (by-product) of one company becomes the raw material of another company. In this work, in addition to the traditional example, the industrial symbiosis is implemented by mixing different food waste streams (including other biodegradable waste) to achieve the optimal concentrations of chemicals in the substrate, before the use in fermentation process or aerobic treatment.

Another distinctive feature is the integration of agriculture into the model as an integral part of food waste management. Since soil is a nutrient receiver (the ecosystem in which the industry must integrate), a special attention is paid to safe (considering pathogens, heavy metals, and persistent organic pollutants) and efficient (considering phytotoxicity control and agronomic value) recycling.

The scientific novelty as well arises from the model of food waste streams that are subjects to the requirements of the Animal By-Products Regulation. Therefore, the management of food waste in the region, according to the model, ensures the control of the spread of diseases as well.

Due to the requirements of the Animal By-Products Regulation applicable to the decision support model, the model is exclusively suitable for the member states of the European Union. However, the application of the model is not limited to the European Union. The management principles depicted in the model would allow achieving optimal food waste management in any region of the world. However, to the author's knowledge, such model has not been published and applied in the world yet.

Practical value of the thesis

The proposed model can be applied to the policymaking, especially regional policy, as more efficient food waste management can be achieved in smaller areas. Based on the results of the model, at the national level, certain pieces of legislation could be amended to empower innovative food waste management alternatives, which cannot be applied due to the current regulation. Additionally, this model can be used by regional waste management administrative units that are operating in a country (e.g., regional waste management centers (RWMC)) or the country itself to formulate regional (certain areas) waste management plans or action plans. By extending the boundaries from the region to state, such a model would help to develop national waste management plans. Based on the model, a regional administrative unit could be formed to collect information on the food waste flows and be directly responsible for managing these flows.

The proposed integrated food waste management model at the regional level would be suitable for companies use. The model would help companies to prioritize the utilization of the material and energy properties of the food waste. Whereas, the waste managers could optimize the waste management processes by using the limit values and waste management schemes provided in the model.

Scope and structure of the thesis

This dissertation consists of an introduction, 3 main chapters, conclusions, and references. The first chapter provides an overview of the legal, practical, and scientific literature. This chapter examines the possibilities of food waste optimization, quality indicators, and their values, parameters that should be controlled, ways to recover energy, produce higher value-added products and/or compost of high agronomic value from by-products (potential waste). Much attention is paid to the review of preventive measures from primary production to consumption. The next section presents the research methodology, including the scientific methods that are used to approbate and apply the model. The third chapter presents the results of theoretical and practical research, approbation results, integrated regional decision support model of food waste management, based on the industrial ecology concept, as well as the algorithm for the application of the model. During the approbation, three significant food waste streams in the Utena region were evaluated. The inventory analyzes of current and planned situations as well as their LCA were performed, and the obtained results were compared in order to substantiate the positive impact of the alternative on the environment. Finally, the conclusions are presented at the end. The main material is presented in 114 pages, including 35 tables and 22 figures. In total, 235 literature sources were analyzed in the dissertation.

I. FOOD WASTE STREAMS, PROPERTIES, MANAGEMENT METHODS, AND REQUIREMENTS: SCIENTIFIC AND PRACTICAL LITERATURE ANALYSIS AND LEGISLATION REVIEW

In order to understand the scale of industrial ecology (IE) application potential for the FW management, various scientific and practical literature sources were analyzed. The key topics that were extensively analyzed were FW sources, FW prevention, starting from the early stage of production to consumption, and production of higher value added products (VAP) from homogeneous FW streams. During the analysis, such FW prevention strategies like the incorporation of microorganisms, fertilization strategies, soft management approaches, artificial intelligence solutions, advanced packaging, smart sensors, ripening and decay control measures, side streams reprocessing to food and non-food possibilities were briefly analyzed. The value added products production analysis from FW was conducted because it is as a way to dematerialize the use of materials that are needed for the economy. Moreover, the by-products utilization for the value added products were included in the analysis, because it can be related to the industrial symbiosis. Furthermore, the idea of industrial symbiosis extends to the level of different biodegradable waste mixing in order to optimize the substrate composition for the optimal use of material and energetic properties.

Separate chapters were dedicated to the FW aerobic and anaerobic treatments, because these processes are the cornerstones of such waste management. In the chapter, the optimization of strategies, optimal parameters of the technologies are shortly discussed. The analysis is carried out because such optimizations lead to the recovery of more value added product (biofuel, compost, bio-based chemicals), which consequently, lead to the reduction of fossil fuel based products and help to dematerialize the material streams.

In the chapter on waste management model, the examples of other authors' models are briefly analyzed. The advantages and disadvantages of the reviewed models were revealed.

During the legislation analysis, common FW management policy was investigated. Special attention was dedicated to the animal by-products (ABP) directive and national quality requirements for the composts that are produced from the biodegradable waste (BDW).

II. METHODOLOGY

2.1. Decision support model and its application algorithm development methodology

This section provides a methodology for the decision support model. The model and its application algorithm have been created based on the theoretical and practical research as well as the approbation results (while analyzing the selected region) (see Fig. 1).

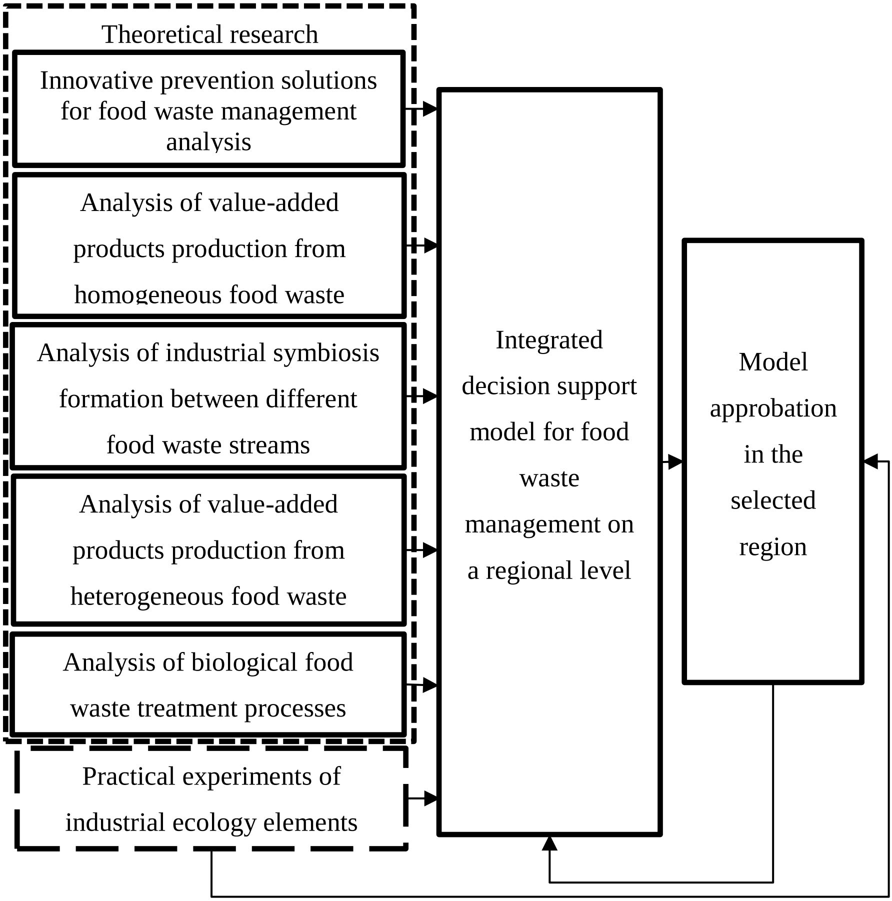

Figure. 1. Industrial ecology concept application for the integrated decision support model of food waste on the regional level development methodology

The application algorithm of decision support model was formed, according to the information, which is needed in order to select suitable FW management alternatives. The information, which is needed, was determined by analyzing the case of Utena region.

The model was as well developed by analyzing one of the Lithuanian regions. The region of Utena was selected as an object for the collection of specific data and the approbation of the model. According to the model, the existing management systems of FW were analyzed, and the problems were identified (for three most significant FW streams). Then, the suggestions were formed, analyzed, and compared to the current situation, according to the model.

2.2. Laboratory research and experimental part: Catering ABP and GW management

Practical experiments were carried out in 3 catering companies, which generate from 9 to 30 kg d^{-1} (approximately 10 t y^{-1}) and exploit Oklin GreenGood 10s (Kliopova et al., 2019) and Green Service bioreactor bio-10 (Green service, n.d.). The experiment was divided into two parts. In the first part of the experiment, the primary compost was produced in all three catering companies, but only one was chosen for further research (due to the higher total nitrogen and total phosphorus, more attractive appearance). In parallel, green waste (GW) primary compost was prepared at the GW composting site.

In the second part of the experiment, the selected ABP primary compost (15%) was co-composted with GW primary compost (85%). The composting occurred in 700-liter bin. The turning frequency was once per week. The sampling was performed by taking 10 specimens from the top, middle, and bottom locations of the collected ABPs1 primary compost in random order and then uniformly mixing these 10 specimens to form one sample. The samples were taken after 60 and 90 days. The samples were delivered in an accredited local and JSC “Jurby Water Tech” laboratories where compost quality parameters were determined. ABP compost that was produced in the centralized treatment plant was sampled in the same manner as the previous samples and delivered to the same laboratories.

2.3. Life cycle assessment methodology

The environmental impacts of the conventional and suggested catering ABP management scenarios were calculated and compared by using the life cycle assessment (LCA) tool. The ReCiPe method at the midpoint level was used to perform the impact assessment based on ReCiPe2008 by Goedkoop et al. (2008) and the updated version ReCiPe2016 by the National Institute for Public Health and the Environment (Huijbregts et al., 2017).

III. INTEGRATED DECISION SUPPORT MODEL ON A REGIONAL LEVEL

3.1. Results of theoretical research: Industrial ecology integration into decision support model

The theoretical research in the preventive measures of FW resulted in helping to define the model structure, controlling parameters, and goals. For example, due to the analysis, the decision was made to include the whole food supply change. Moreover, the emphasis was made to firstly divert food back to the supply change, leading to optimal material properties utilization, and therefore, the reduction of primary food production scale. As more material is diverted for consumption, the need for intensive agriculture reduces, resulting in environmental impact reduction on the regional level. The conducted analysis of FW prevention methods (see the first chapter) gave insight that these methods are very diverse, and it is difficult to find a single limiting parameter that would be suitable for all solutions. Therefore, a simple prevention goal was chosen in the model. Food loss (X_n) at different points of the supply chain (n) is illustrated as follows: $X_n \rightarrow 0$. However, the sophisticated life cycle assessment tools allow measuring the positive effect of such preventive methods.

Although prevention measures allow food to be kept in the food supply chain, some of the side flows can be managed to be diverted back to the supply chain simply by producing value-added products. Therefore, the analysis of scientific literature in sub-chapter 1.2. influenced to distinguish arrows, which show the return of materials back to the supply chain. Moreover, the analysis has shown that these side flows can be exploited for non-food value added products; thus, the model was formed accordingly. Moreover, due to the conducted analysis, the production of value added products was separated into those produced from homogeneous and heterogeneous raw materials. Such separation was based on the notion that edible value added products are mostly produced from homogeneous flows, while non-edible, from the heterogeneous FW. Since value-added products produced from heterogeneous FW streams are mostly energy carriers and the materials that are being accumulated in the cells of microorganism (e.g., bio-plastic), in the decision to support model, this production is illustrated in the block of waste treatment.

In search of industrial ecology elements application possibilities, the significant potential of industrial symbiosis was found during the theoretical research. As a result of analysis, the industrial symbiosis block was adopted in the model. The idea behind such block is to mix different FW streams in order to get the optimal values of processing parameters in bio-conversation block and/or composting stages, allowing to fully exploit material and energetic properties, which finally lead to the dematerialization of material that is needed for the economy.

Since anaerobic digestion of biodegradable waste is a key technology, significant research towards the optimization of the processes was carried out. As a result of the theoretical research, the bio-conversation block was added to the model. The analysis has as well provided parameters and values for optimal anaerobic digestion process, which are included in the model (see Table 1). It was assumed that the parameters and values are as well suitable for the production of other value-added products from heterogeneous FW. The block was called bio-conversation, since not only biogas, but other types of biofuels can be fermented. Moreover, the bio-conversation of heterogeneous FW can be adapted for the value-added product production like bio-plastic.

Table 1. Approximate optimal values for microbes during the fermentation

Parameter	Optimal value	Source
Acetic acid concentration	> 0.8g/l	Zhang et al., 2014
Propionic/acetic acid	> 1.4	Zhang, 2014
pH	6.5–7.2	Mpofu et al., 2020
C/N	20–30	Siddique, Wahid, 2018
Available C and N ratio	11–15	Wang et al., 2017
Particle size	0.6 mm	Izumi et al., 2010
NH_3	< 1.7–14 g/l	Li et al., 2020
H_2S	> 125 mg/l	Ariunbaatar at al., 2016
Organic acids/Alkalinity	> 0.5	Zuo et al., 2015
Oleic acid	< 50–75 mg/l	Dasa et al., 2016
Palmitic acid	< 1100 mg/l	Palatsi et al., 2009
Stearic acid	< 1500 mg/l	Palatsi, 2009
Zinc (Zn)	0–5 mg/l	Guo et al., 2019
Chromium (Cr)	> 12 mg/l	Jha, Schmidt, 2017
Copper (Cu)	0–100 mg/l	Guo, 2019
Cadmium (Cd)	0.1–0.3 mg/l	Guo, 2019
Nickel (Ni)	0.8–50 mg/l	Guo, 2019
Iron (Fe)	0.28–200 mg/l	Molaey et al., 2018
Sodium (Na)	< 350 mg/l	Zhang, 2014
Calcium (Ca)	< 2800 mg/l	Bożym et al., 2015
Magnesium (Mg)	< 2400 mg/l	Bożym et al., 2015
Potassium (K)	< 3000 mg/l	Bożym, 2015
Chlorophenols	$\rightarrow 0$	Puyol et al., 2012

Due to the conducted analysis, the decision was made to include technology adaptation block in the waste treatment stage. This selection of proper treatment or pretreatment technology would allow faster rates of material and energy recovery.

Similarly, the composting was analyzed in greater detail, as it is a technology allowing material to return to the cycle. The analysis resulted in determining the emission goals for the composting process. By reducing the emission (carbon, nitrogen, phosphorus, potassium), the materials remain in the compost, which further can be utilized in the agriculture.

3.2. Results of the practical research

During the development of the model, the practical experiments of industrial symbiosis and the dematerialization elements application were performed by analyzing the catering companies ABP management case. The aim of the first experiment was to evaluate the quality and contamination of the produced primary and matured compost as well as the technical feasibility of the technology. During the second experiment, the possibility to form an industrial symbiosis between the produced primary composts of animal by-products and GW was evaluated.

Table 2. Quality of maturated GW and ABP mixture compost as well as separate primary composts of GW and ABP

	Units	Primary GW compost	Primary ABP composts			GW and ABP compost
			ABP1	**ABP2**	ABP3	
Dry matter	%	66.18	88.92	84.21	75.77	58.18
Organic matter	% DM	18.31	83.22	88.34	92.89	20.32
Total Nitrogen	% DM	0.66	1.81	2.38	1.92	1.36
Total Phosphorus	% DM	0.71	0.39	0.65	0.54	0.93
Total Potassium	% DM	0.62	1.44	1.26	1.02	0.76
Conductivity	mS cm^{-1}	1.04	5.77	5.40	5.0	1.1
Chlorides	ppm AR	471	7155	9240	9797	298
Sulphates	ppm AR	628	1820	1089	987	808
Biodegradability	mg kg^{-1}	486	80892	42970	41190	82
Cadmium (Cd)	mg kg^{-1} DM	0.25	-	0.01	-	0.3
Lead (Pb)	mg kg^{-1} DM	14.6	-	2.5	-	17.7
Mercury (Hg)	mg kg^{-1} DM	0.001	-	0.0	-	0.0
Chromium (Cr)	mg kg^{-1} DM	12.2	-	1.97	-	14.8
Zinc (Zn)	mg kg^{-1} DM	145	-	28.5	-	176.9
Copper (Cu)	mg kg^{-1} DM	21.7	-	9	-	27.5
Nickel (Ni)	mg kg^{-1} DM	5.6	-	1.47	-	69

After an intensive composting experiment of animal by products in catering company had been carried out by applying Oklin technology, high agronomical value primary compost was obtained. The produced primary compost had high concentration of organic matter, total nitrogen, water soluble phosphorus, and potassium. Humic and fulvic acid concentration were as well high, indicating the occurrence of the composting process. In addition to this, the investigation of contamination by persistent organic pollutants, impurities, heavy metals, and pathogens have shown that the primary compost is free of pollutants. However, the primary compost was phytotoxic, and even after sole maturation, the compost remained phytotoxic.

The second experiment included composting at the source of generation and diversion of ABP primary compost to the nearest GW composting site. As it can be seen in Table 3, the values of parameter associated with phytotoxicity were stabilized. For example, the conductivity decreased to 1.1 mS/cm (optimal range 0.6–2.0 mS/cm), chloride concentration to 298 ppm as received (AR) (optimal range < 300 ppm AS), biodegradability to 82 mg kg^{-1} (optimal range < 4000 mg kg^{-1}). The poor GW compost was amended by the ABP compost, resulting in an increase of organic matter (20.32% dry matter (DM)), total nitrogen (1.36% DM), total phosphorus (0.93% DM), and potassium (0.76% DM) (see Table 2).

Table 3. Composting process parameters and their limit values in the model

Quality, phytotoxicity, and contamination parameters	**Units**	**Limit values**
Quality parameters		
NPK sum	% DM	> 2.5
Organic matter (OM)	% DM	> 20
Phytotoxicity parameters		
Electrical conductivity	mS cm^{-1}	< 2
Biodegradability	mg kg^{-1}	< 4000
Contamination parameters		
PCBs	mg kg^{-1} DM	< 0.4
PAHs	mg kg^{-1} DM	< 4.0
Impurities with a particle size greater than 2 mm	% DM	≤ 0.5
Escherichia Coli	CFU kg^{-1}	≤ 1000
Cadmium (Cd)	mg kg^{-1} DM	2
Lead (Pb)	mg kg^{-1} DM	130
Mercury (Hg)	mg kg^{-1} DM	1
Chromium (Cr)	mg kg^{-1} DM	70
Zinc (Zn)	mg kg^{-1} DM	800
Copper (Cu)	mg kg^{-1} DM	300
Nickel (Ni)	mg kg^{-1} DM	50

During the experiment, while analyzing compost quality indicators, it was concluded that the quality of compost is significant in the management of the FW, according to the concept of industrial ecology. Controlling values of parameters, like those associated with phytotoxic parameters, quality, contamination, allows recycling more nutrients by safe manner back to the soil.

For this reason, these parameters along with the required values were included in the block of composting. Moreover, the experiment as well as the theoretical research revealed that it is reasonable to include other BDW streams into the management. Therefore, in a model, if other types of BDW can help to optimize the usage of material and energetic properties, they can be included. In a model, the BDW streams are shown, entering the industrial symbiosis block.

The quality, contamination and phytotoxicity parameters, and their limit values (LV) that are presented in Table 3 are integrated into the decision support model. These parameters and their LV are determined based on Staugaitis et al. (2011, 2016) and Staugaitis, Vaišvila (2015) as well as Lithuanian law for fertilizers. Based on these studies, LV for the sum of total nitrogen, phosphorus and potassium (NPK) (> 2.5% DM), and OM (> 20% DM) were established. E. Coli concentration (≤ 1000 colonies forming units (CFU) per kg) was chosen as a market for the biological contamination. The limit values for heavy metals basically were taken from the legislation, increasing only the threshold for zinc (800 mg kg^{-1} DM). Polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbon were included in order to control the pesticide circulation between the waste and agricultural systems.

3.3. Model application algorithm: A decision support model of industrial ecology concept for integrated food waste management at the regional level

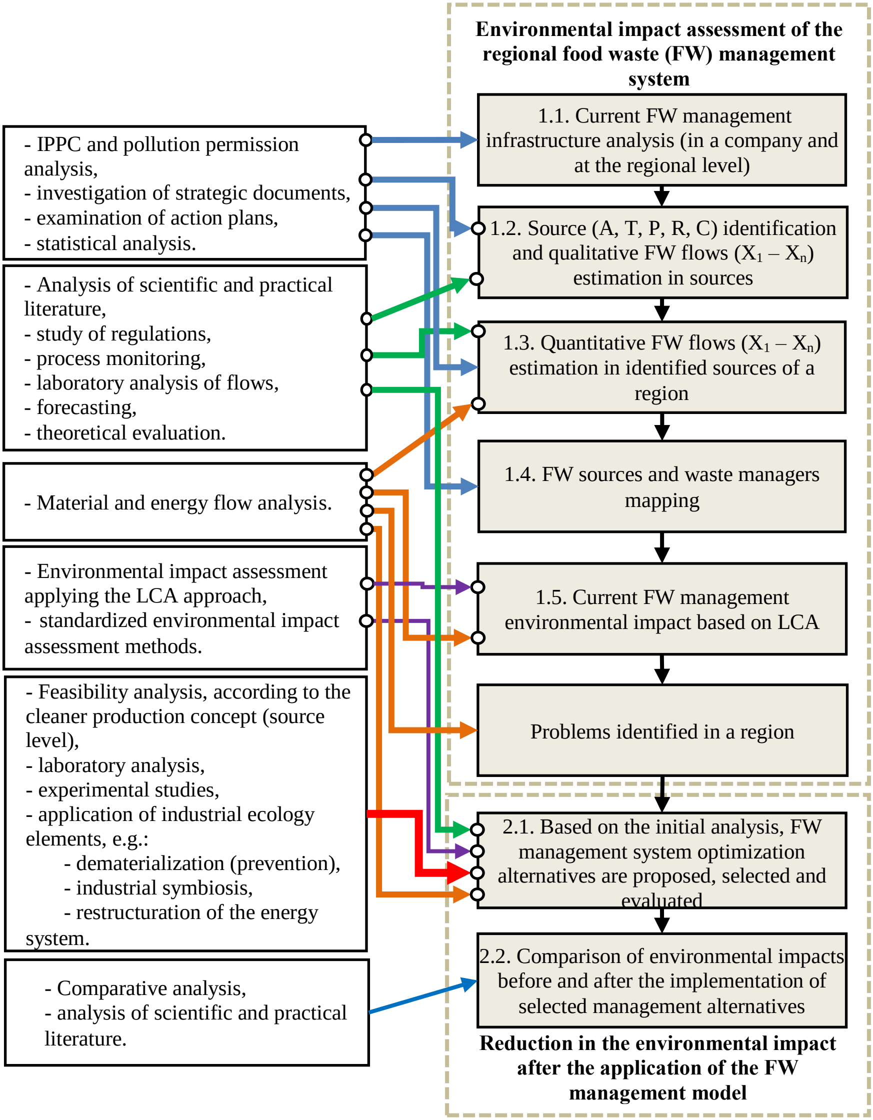

Figure 2. Model implementation stages for the FW management system optimization

Figure 2 illustrates the key steps, strategies, methods, and tools that are used to assess the current situation and select the most appropriate management alternative for FW management in the region. Accordingly, 1.1.–1.5. shows the analysis of the current situation, while 2.1.–2.2. points are related to the analysis of alternatives.

3.4. Decision support model based on the industrial ecology concept for integrated food waste management at the regional level

In the model, three major directions depict the food supply chain. The direction from the top to the middle represents plant origin food, while the direction from the bottom to the middle represents the supply of animal origin food. When plant and animal origin food arrows meet, it shows that these different origin materials are mixed to form composite foodstuff. The model starts at the primary agricultural production; this stage produces materials for both human and livestock consumption. In parallel, the primary production of animal origin food begins as well, but the stage is located at the bottom of the illustration (see Fig. 3).

The waste, by-products, and animal by-product streams, arising during the supply of goods, are depicted on the left of the main plant and animal origin food supply arrows. Basically, $X_n \rightarrow 0$ means that during the management of side streams, the prevention is a preferable action to be taken, allowing the elimination of a side stream, and therefore, leaving more food in the supply chain.

When the possibilities to prevent food losses as well as produce value added products (VAP) from separate streams are fully exploited, the remaining side flows are diverted to a block where mixing of different FW or other biodegradable waste streams occurs. Since the possibilities to mix flows will not be ideal, certain adjustment or optimization of existing infrastructure and technology will be necessary. In this block, the industrial symbiosis and dematerialization elements will only be adopted if the environmental impact in terms of life cycle assessment is positive $\Delta LCA > 0$. The mixing occurs following the optimal concentrations of chemical compounds in a bioconversion stage and/or limit values (LV) of contamination and quality parameters in composting stage. In the bioconversion stage, individual as well as groups of chemical compounds are shown. For example, heavy metals (HV), persistent organic pollutants (POP), volatile fatty acids (VFA), volatile solids (VA), fatty acids (FA) represent the groups of chemical compounds, while H_2S and NH_3 are examples of individual chemical compounds. The expanded list of the chemical compounds, their groups, ratios, and optimal values (OV) for the bioconversion are presented in Table 1. The composting stage is comprised of emission minimization goals and the control of HV, phytotoxicity, pathogens, POP, impurities, OM, and NPK, according to the established LV in Table 3.

Mayor ideas of the model in brief:

- Emphasis on diverting as much edible materials as possible:
    - Less sophisticated technologies are required; food is easier to produce than the chemical compounds;
    - Less sophisticated technologies cause lower environmental impact;
    - Food products from the food supply by-products are more acceptable to a consumer;
    - Diversion of more food material for a consumer results in the reduction of intensive agriculture.
- Holistic approach to FW management:
    - Communication of food saving idea throughout the supply change allows to set the pace for prevention;
    - Evenly applied efforts throughout all stages ensure sound management of FW;
    - Even small measures that are simultaneously applied in different parts of the supply change accumulate substantial environmental impact reduction.
- Industrial symbiosis element implementation from different perspective:
    - Substrate composition is balanced by compiling necessary material properties from different FW streams in order to optimize the bioconversion and composting processes;
    - FW streams are used as amendments to optimize the bioconversion and composting processes.
- Significant focus of compost quality and contamination:
    - Conservation of NPK nutrients in compost leads to the reduction of artificial fertilizers (recycling adds to dematerialization);
    - As more NPK is conserved, the emissions are reduced;
    - The control of parameters and their values that are accountable for phytotoxicity results in ensuring agriculture productivity;
    - Increase in agronomical compost value leads to more extensive usage among the farmers;
    - Increased application of compost results in carbon sequestration, water retention, etc.;
    - Control of contamination leads to the safe recycle of compost.

- Highlighted fermentation processes:
    - Optimal concentration of materials in substrate allows to achieve dematerialization goals;
    - The production of various energy carriers and/or value added products (from heterogeneous streams) leads to reduced fossil fuel consumption (dematerialization);
    - The control of heavy metal concentration allows to utilize effluent for compost production;
    - Technology adaptation allows coping with recalcitrant substrates.
- $LCA_n – LCA_{n+1} \rightarrow max$ fosters implementation of FW management innovation, because a significant gap between the current and planned situations can only be created by applying completely different approaches.

The objective function is the optimal utilization of food waste material and energetic properties.

The optimization criteria include the reduction of environmental impact with the fastest return on investment (project payback period < 3.5 years in terms of funds allocated by the entity).

The object is the food waste and its management system.

The system boundaries are food waste, including other biodegradable waste streams, which could act as stabilizing, catalyzing materials for treatment processes or simply have a potential to increase nutrients recycle.

The end of the model is when at a given time, all MA management alternatives with a payback period of < 3.5 years (in terms of funds allocated by the entity) are implemented.

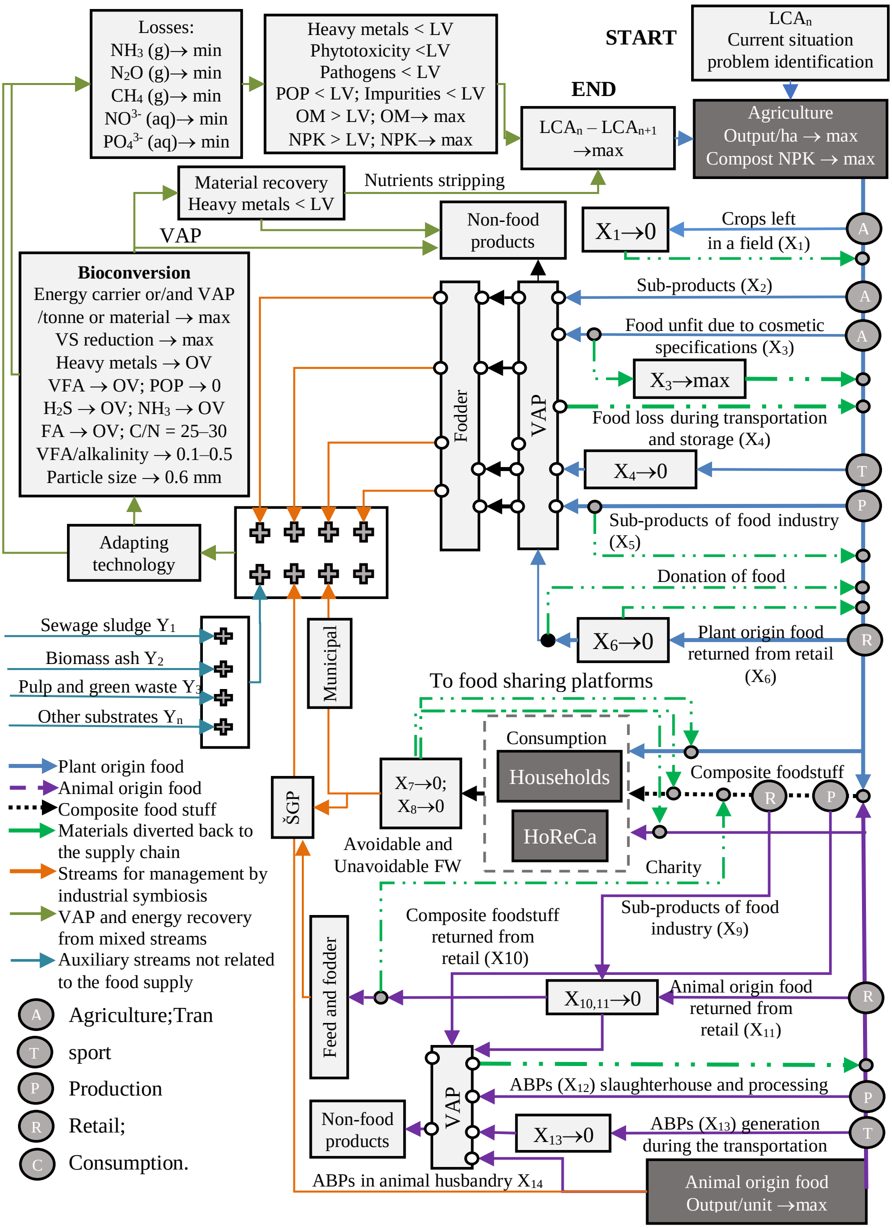

Figure 3. Integrated decision support model for the FW management

3.5. Model approval for the selected food waste management alternatives

The decision support model was approbated for three significant MA flows in the Utena region. The streams were selected according to the specifics of the region and the fact that the approval of the support model would occur in different blocks of the model, such as value-added product manufacturing, industrial symbiosis, fermentation, and aerobic treatment units.

According to the model and its application algorithm, during the approval, two different control scenarios are compared based on the analysis of the LCA. An inventory analysis of the current FW stream management (at the regional or company level) is performed first, and then it is followed by an inventory analysis of the selected alternative.

3.5.1. Adding value by producing pet feed instead of the biogas and compost

According to the model, current (anaerobic digestion of ABP) and planned (production of pet feed from the ABP) management approaches were measured by applying the LCA method. After the LCA analysis of suggested pet food production and current ABP management alternatives was carried out, it has been found that the environmental impact of the system may be significantly reduced. At the midpoint level, the overall environmental impact reduced from 4.13 MPt to -2.62 MPt (see Table 4). While the analysis in midpoint level has shown reduction in 15 out of 18 environmental impact categories (see Fig. 4).

Table 4. Comparison of pet food production alternatives with current anaerobic treatment of ABP by the means of LCA

	Units	Planned situation	Current situation
Total	MPt	-2.62	4.13
Human health	MPt	-2.04	3.97
Ecosystems	MPt	-0.574	0.159
Resources	MPt	0.00435	0.00102

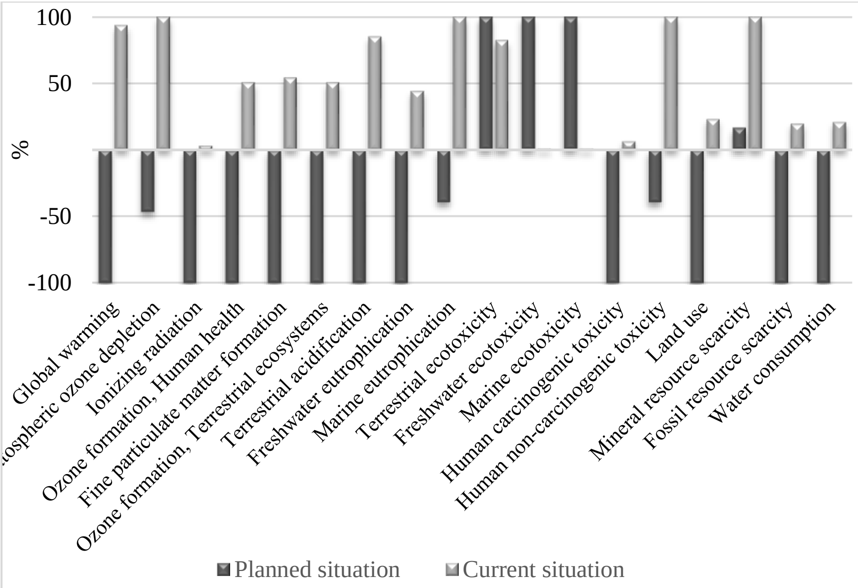

Figure 4. LCA analysis and comparison of pet feed production and anaerobic ABP treatment alternatives at the midpoint level

3.5.2. Optimization of municipal food waste management in the region

The decision support model was approbated for the Utena region municipal FW management system. According to LCA inventory results of the management alternatives, the LCA of current and planned management methods were conducted. At the endpoint level, the overall environmental impact reduced from 16 MPt to -350 Pt (see Table 5). While the analysis at the midpoint level has shown reduction in 16 out of 18 environmental impact categories (see Fig. 5).

Table 5. LCA analysis and comparison of current and planned Utena municipal FW management alternatives at the endpoint level

	Units	Planned situation	Current situation
Total	Pt	16	-350
Human health	Pt	14.7	4.83
Ecosystems	Pt	1.33	-355
Resources	Pt	0.0206	-0.0231

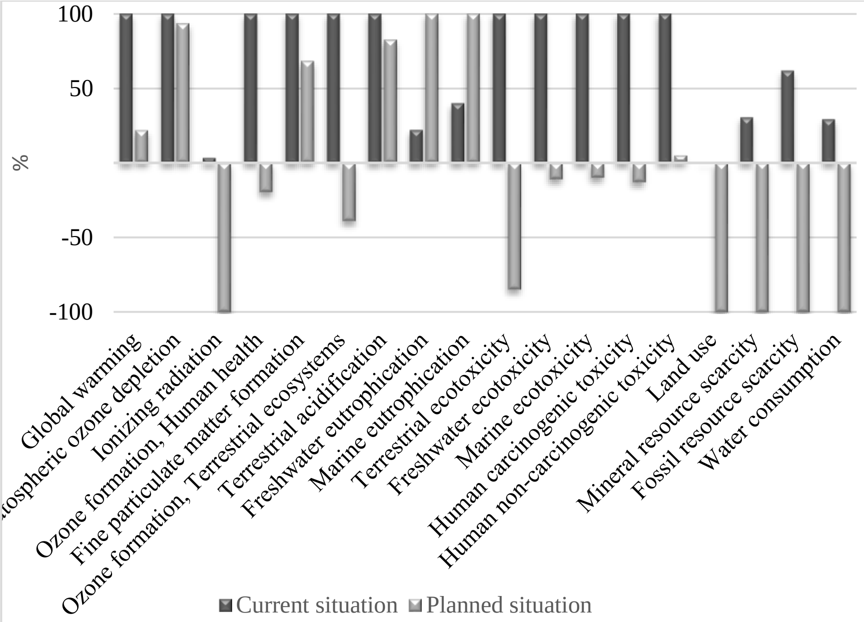

Figure 5. LCA analysis and comparison of current and planned Utena municipal FW management alternatives at the midpoint level

3.5.3. Optimization of catering food waste management

The decision support model was approbated for catering ABP management. The alternative approach was selected; the LCA inventory of current (centralized ABP composting) and planned (intensive composting at the source of ABP generation) management approaches were conducted.

Table 6. LCA analysis and comparison of current and planned catering ABP management alternatives at the endpoint level

	Units	Planned situation	Current situation
Total	kPt	-22.3	-33.4
Human health	kPt	0.297	0.134
Ecosystems	kPt	-22.60	-33.50
Resources	kPt	0.00717	0.000646

The LCA comparison of current management and planned alternatives revealed that at the endpoint level, the overall environmental impact was reduced by 33% (see Table 6). While the LCA analysis at the midpoint level has shown reduction in 12 out of 18 environmental categories (see Fig. 6).

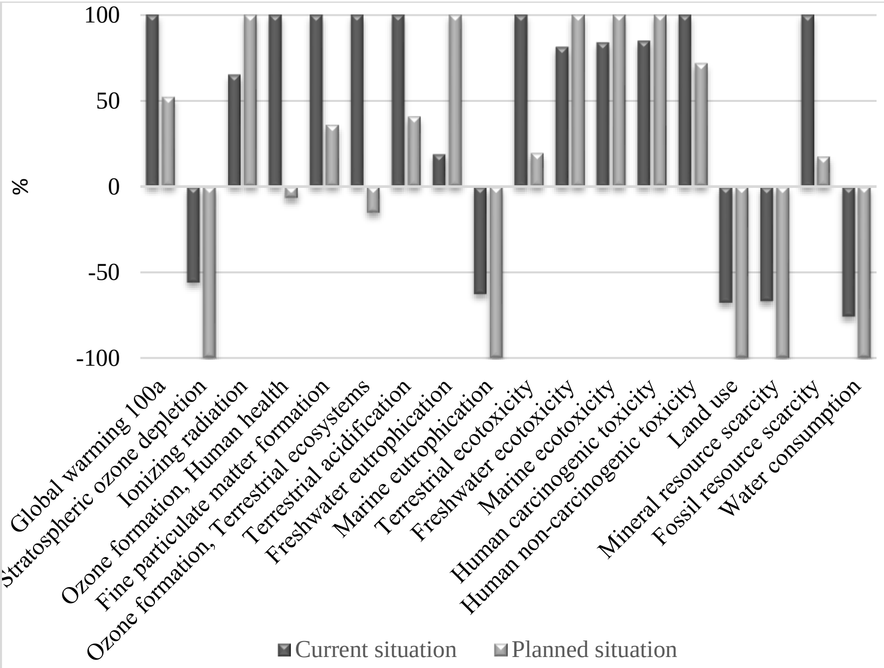

Figure 6. LCA analysis and comparison of current and planned catering ABP management alternatives at the midpoint level

CONCLUSIONS

1. After legislative, practical, and scientific literature review in the field of food waste streams, properties, and their management methods, systems, and models was carried out, it has been determined:

- The identification of food waste sources and their quantification has shown that the food waste needs to be assessed throughout its life cycle, including by-products and animal by-products. The latest preventive measures (dematerialisation) in the food waste management are based on the application of information technology. Other smart solutions include the transformation of food waste, by-products, and animal products first into food, food supplements, and finally, other higher value-added products, including energy carriers. There is a high potential to optimize anaerobic and aerobic process by controlling the substrate composition.
- In strategical documents, there remains a general tendency to avoid food waste and manage unavoidable food waste through innovative measures that allow moving towards the closed material loop. Depending on the nature of food waste, different requirements for treatments are applied. In Lithuania, the fertilizer products that are made from food waste are a subject to strict contamination requirements, but only a few quality parameters are required, and their limit values are relatively low.
- Most waste management models that have been developed by other researchers are designed to manage only municipal food waste, often including supermarket food waste; the application of industrial ecology to food waste management is not analyzed.

2. After the theoretical and practical experiments on the application of industrial ecology elements were carried out, the following guidelines for the model development have been established:

- The usage of results that were obtained during the theoretical research on industrial ecology elements application: the structure of the model is aligned with the food supply chain. Agriculture, transportation, production, retail, and consumption have been distinguished as the main sources of food waste, assigning the most relevant food waste streams to each of these sources and setting management objectives for them. It encompasses the inclusion of higher value-added products production, excluding sources where these products can be extracted from homogeneous and heterogeneous waste streams; the extension of anaerobic process to bioconversion process due to the possibility to recover different energy carriers and/or to produce higher value-added products; different food waste mixing incorporation as a way to optimize bioconversion and aerobic treatment processes; the integration of the bioconversion process limiting parameters (optimal concentrations of substances); the identification of aerobic emissions and setting their reduction targets.

o The usage of results that were obtained during the practical research of the industrial ecology elements application: a management system for catering animal by-products based on the elements of dematerialization and industrial symbiosis was developed. It allows catering animal by-products to be managed at the source of generation by the production of the primary compost, but further reduction of environmental impact and process optimization can be achieved by diverting the primary compost to a nearest green waste composting site to create a synergy in mixtures with green waste primary compost. As a result of these experiments, it has been decided to include compost contamination and quality parameters and their limit values in the model as the limiting parameters. The contamination by contaminants, heavy metals, microbiological, and persistent organic pollutants and limit values for these parameters are included in the model. The basic quality parameters and their limit values include organic matter (> 20% of dry matter), nitrogen, phosphorus, and potassium (sum of NPK > 2.5% of dry matter). Moreover, the biodegradable waste streams that are not food waste streams are included in the model; food flows of plant and animal origin are separated.

3. A decision support model has been developed for the optimal management of food waste streams at the regional level, integrating elements of industrial ecology concept: from dematerialization by applying cleaner production prevention methods to the industrial symbiosis, interaction with the biosphere, and energy system restructuration. The decision support principle of the model and its application algorithm is the improvement of existing food waste management based on the analysis of the existing system. The model prioritizes food prevention solutions in the food supply chain, distinguishes animal by-products on the basis of disease prevention, emphasizes the integration of food waste management with agriculture, the principle of the integrated approach and cascading. The management of unavoidable food waste is carried out by mixing or combining biodegradable waste of different nature in order to comply with the limit values of parameters that are set in the bioconversion and aerobic treatment processes. The solutions to prevention and production of higher value-added products are encouraged by the widest possible difference in the environmental impact between the current and planned situation. The driver of the implementation of solutions for food prevention and production of higher value-added products is the maximum environmental

impact difference between the current and planned situation (LCA_n – $LCA_{n+1} \rightarrow max$).

4. After approving and at the same time applying the proposed model in Utena region, 3 food waste management alternatives were selected and compared in the life cycle with the existing management systems. In the case of the first alternative, the environmental impact on the management system of meat processing animal by-products was reduced from 4.13 to -2.62 MPt, and the reduction was observed in 15 out of 18 environmental impact categories. In the case of the second alternative, the environmental impact of the municipal food waste management system was reduced by 23 times, and the reduction was observed in 16 out of the 18 environmental impact categories. In the case of the third alternative, the environmental impact of the management of catering animal by-products was reduced by 33%, and a reduction was observed in 12 out of 18 environmental impact categories. During the approval and based on its results, it was accepted to limit the selection of alternatives in a model, according to the payback period of the project (< 3.5 years in terms of funds allocated by the entity) to estimate only total nitrogen, phosphorus and potassium, and use life cycle assessment methodology.

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