EFFICIENT ENERGY EXTRACTION FROM ORGANIC WASTE IN CIRCULAR SYSTEMS

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ABSTRACT

In the contemporary focus on sustainability, organic waste management is identified as a crucial challenge. An in-depth exploration of energy recovery from organic waste is presented in this study, framed within the context of a circular economy and guided by bioeconomy principles. A series of experiments, modeled mathematically, were conducted to investigate various compositions of organic waste under controlled conditions, with the aim of identifying optimal scenarios for maximizing energy generation. The efficient harnessing of organic waste as a renewable energy resource, in alignment with sustainable bioeconomic strategies, was the core objective. The findings of this study unveil the significant potential of converting organic waste into a sustainable energy source. Through the fine-tuning of specific factors and judicious resource management, a marked improvement in energy recovery was demonstrated. This approach is shown to be not only feasible but also imperative for environmental conservation. The research underscores how bioeconomic principles can transform the management of organic waste, turning it into a valuable asset for global sustainability. Ultimately, this study provides a compelling view of how the bioeconomy can reshape methods of recovering energy from organic waste, thereby paving the way for a more sustainable and environmentally responsible future.

1 INTRODUCTION

The management of organic waste is a pivotal issue within the context of sustainability, attracting significant scientific interest due to its implications on environmental stability and the integrity of natural ecosystems. Globally, the production of organic waste is increasing across various sectors, including the food industry, agriculture, and livestock, with a substantial portion still being sent to landfills, particularly in developing countries. Such practices not only isolate nutrients and energy but also disrupt natural material cycles, undermining ecosystem balance (Tomić & Schneider, 2018; Li et al., 2010). Historically, waste management strategies have primarily focused on linear approaches, such as landfilling and incineration, which are often associated with significant energy inputs and greenhouse gas emissions. However, these methods have been reevaluated considering their environmental impact and the inefficiency in resource utilization. The circular economy model offers a more sustainable framework, promoting the recovery and regeneration of materials and energy within a closed-loop system, thereby minimizing waste generation (Malinauskaite et al., 2017). Energy recovery from waste, especially through processes like anaerobic digestion, has been identified as a critical component of sustainable waste management practices. Tomić and Schneider (2018) emphasize the role of energy-from-waste within the circular economy, highlighting its potential to close material loops and enhance energy efficiency. This approach is not only environmentally advantageous but also aligns with the principles of resource conservation and energy security. The agricultural sector, a major producer of organic wastes such as crop residues and animal manure, has seen innovative applications of circular economy practices. Barros et al. (2020) focus on converting agricultural waste to energy, underscoring the dual benefits of waste reduction and energy production, integral to sustainability in agricultural processes where waste valorization plays a pivotal role. In the realm of industrial strategies, energy

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conservation and waste reduction are vital for transitioning towards a circular economy. Li et al. (2010) discusses the incorporation of circular economy principles in China's process industries, which have significantly contributed to energy savings and reduced environmental footprints through enhanced waste management and recycling initiatives. Sanguino et al. (2020) explores the broader implications of waste management on sustainable development and energy conservation. Their review covers current trends that integrate circular economy practices with sustainable development goals, focusing on maximizing energy efficiency and minimizing ecological impacts. The role of circular economy strategies in facilitating clean energy transitions has become increasingly relevant, particularly under global challenges such as the COVID-19 pandemic. Su and Urban (2021) discuss how circular economy approaches can provide new opportunities for clean energy transitions, promoting environmental resilience and sustainable growth. Additionally, the integration of municipal solid waste management with waste-to-energy technologies in Europe is detailed by Malinauskaite et al. (2017). Their work emphasizes the importance of waste-to-energy systems within the context of a circular economy, highlighting the benefits of energy recycling and the strategic redirection of waste from landfills to energy production facilities. These literature insights collectively frame the potential and necessity for implementing efficient energy extraction practices from organic waste within circular systems, setting the stage for this study's focused investigation on anaerobic digestion as a sustainable solution.

Building on the foundational insights provided by the literature, this research aims to explore anaerobic digestion as an effective method for organic waste treatment within a circular economy framework. The primary objective is to evaluate the process efficiency and energy yield from the anaerobic digestion of various organic waste streams, thereby contributing to sustainable waste management practices and the production of renewable energy. By focusing on the optimization of anaerobic digestion processes and the detailed analysis of energy flows and interactions within the system, this study seeks to enhance the efficiency of organic waste conversion to biogas. This research not only aims to provide a technical evaluation of energy recovery potentials but also to assess the environmental and policy implications of implementing circular economy practices in waste management.

2 MATERIALS AND METHODS

To comprehensively depict and understand the movement of materials through the system, including their flows, characteristics, transformations, and interactions, a conceptual model has been established. This model serves to illustrate and comprehend the structure of elements and relationships within the formulated system. It is particularly useful in the specialized approach to anaerobic digestion, where it acts as a foundation for visualizing process flows and interactions within the system that converts organic waste into biogas. Furthermore, a mathematical model has been developed to enable efficient management and quantification of the multidimensional and complex processes. The mathematical model provides a basis for the creation of material and energy balances of the system itself and for the quantification of ongoing processes. By integrating various aspects of the system, the mathematical model facilitates the creation of material and energy balances, thereby precisely quantifying and evaluating the efficiency of organic waste conversion into biogas. Focusing on the efficiency evaluation of this conversion, including a detailed analysis of process parameters and their impact on the ultimate biogas yield, is crucial for complementing the conceptual model and enhancing understanding of the complex processes within the system. The mathematical model specifically serves to account for the incorporation of raw materials, energy leakages, and provides a comprehensive framework for understanding the efficacy and dynamics of the system.

2.1 Conceptual model

In the forthcoming chapter, a conceptual model for the integrated management of organic waste is elaborated upon, utilizing circular economy principles with a focused exploitation of the chemical energy stored in organic waste. The model posits a closed-loop system that enables the perpetual recycling of organic materials and energy. The flow of organic material through the system undergoes a series of biological transformations during anaerobic digestion, where microorganisms break down

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biodegradable material in the absence of oxygen. This process not only results in the production of biogas—a mix of methane and carbon dioxide which can be combusted for heat and power—but also generates digestate, a nutrient-rich substance that can be used as organic fertilizer. The digestate is reintroduced into the system, thus closing the loop by acting as a raw material that contributes to soil fertility. The efficacy of this model is contingent on several factors, including the purity of the organic waste streams and the efficiency of the anaerobic digestion process. While the model promotes sustainability by reducing waste and producing renewable energy, it also faces limitations, such as the requirement for significant initial investment in infrastructure and the need for careful management to maintain the balance of the biological processes involved.

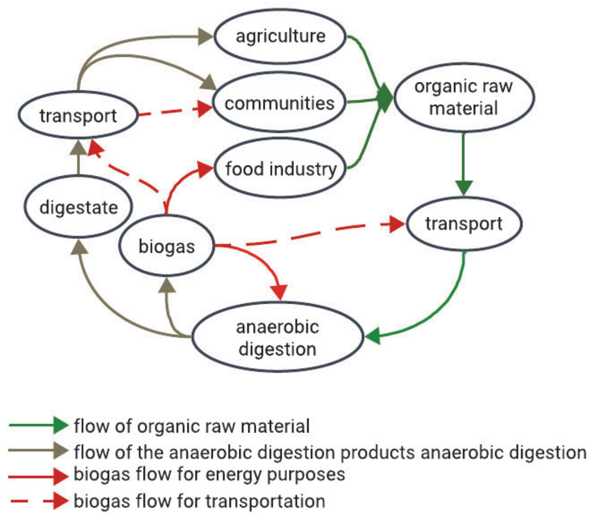

Figure 1 Diagram of the Conceptual Model for Circular Economy in Organic Waste Management, illustrating the closed-loop flow of organic materials and the intertwined energy cycle facilitated by anaerobic digestion

To enhance understanding of the model's role and significance, it is essential to scrutinize the specific sources of organic waste in the analyzed geographic area. Organic waste from households, agriculture, and the food industry constitutes the primary inputs into this system. The sorted organic waste is then transported to the treatment facility where the anaerobic digestion takes place. The biogas produced is prioritized for energy needs within the treatment and transport facilities of organic raw materials, and excess energy is channeled to support the food industry operations. This approach not only illustrates the principles of circular economy but also underscores the model’s potential for optimization and the capacity to effectively manage resources while maximizing renewable energy production from organic waste.

2.2 Mathematical model

Every model, regardless of its complexity or field of application, is founded on certain assumptions that define its fundamental capabilities and limitations. These assumptions often represent simplified versions of reality which facilitate efficient modeling and simulation but can also impose certain constraints on the interpretation of the results. Table 1 presents the system boundaries within which the model can be considered valid. By considering these elements, the possibilities and limitations of the model are better understood, which is crucial for its proper application and interpretation of results.

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Table 1: Assumptions of the formed model for integrated management of organic waste using the principles of circular economy

Assumption 1.	The origins of organic raw materials encompass the populace and their assorted activities, agricultural practices, and selected sectors of the food industry.
Assumption 2.	The biological treatment of organic raw material used for energy recovery is anaerobic digestion.
Assumption 3.	The anaerobic digestion process occurs in a thermophilic temperature range at 60°C, in a continuous anaerobic digester, with a hydraulic retention time of 14 days.
Assumption 4.	The conversion rate of the digestate is 0.4, meaning that 40% of the initial amount of organic matter treated by the anaerobic digestion process is converted into digestate.

To assess the efficiency of a circular economy within a closed system (city or region), a mathematical model has been developed. This model encompasses an analysis of integrating individual system elements and a material-energy analysis of the formed closed loop.

For a proper understanding of the dynamics and relationships within the mathematical model, it is crucial to be familiar with the input raw materials and their specific characteristics. In urban settings, intensive human activities generate three basic categories of organic waste: the organic fraction of solid municipal waste, waste from the maintenance of urban green areas such as parks, and secondary sludge from wastewater treatment processes. Agriculture also serves as a significant source of organic waste, with the model giving particular attention to waste from crop harvesting, fruit tree pruning, and livestock by-products. Similarly, the food industry, including sectors like the dairy industry and fruit and vegetable processing, plays a key role in producing substantial amounts of organic waste on the analyzed territory. This waste presents both a challenge and an opportunity for sustainable resource management, fostering the development of strategies for its valorization through various processing techniques.

Table 2 presents the specified organic raw materials generated in the area under consideration, their characteristics (carbon content, nitrogen content, C/N ratio, dry matter content, moisture content), and the quantities generated on an annual basis (available amounts).

Table 2: Characteristics and annual production of organic raw materials in the analyzed region

Organic Raw Material (Source)	**Carbon content C [%]**	**Nitrogen content N [%]**	**C/N ratio**	**Moisture content W [%]**	**Dry matter content X(1-W) [%]**	**Generated quantities Q [t/year]**
Raw material 1 (S_1)	C_1	N_1	C/N_1	W_1	X_1	Q_1
Raw material 2 (S_2)	C_2	N_2	C/N_2	W_2	X_2	Q_2
Raw material 3 (S_3)	C_3	N_3	C/N_3	W_3	X_3	Q_3
….	...	...	...	...	...	...
Raw material N (S_n)	C_n	N_n	C/N_n	W_n	X_n	Q_n

The generated quantity of organic matter in the considered system that can be treated, denoted a Q_{OW}, arises as the sum of the quantities of individual types of organic raw material waste in the observed territory *(Q_1, Q_2, Q_3,… Q_n)* and can be described by Equation (1):

$$Q_{ow} = Q_1 + Q_2 + Q_3 + \cdots + Q_i + \cdots + Q_n = \sum_{i=1}^{n} Q_i \quad (1)$$

where $i, n \in N$

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2.2.1. Defining optimal conditions for the treatment of organic raw materials

The conditions under which organic raw materials are treated directly impact the efficiency of the process and the quality of the end products. Precisely defining these conditions ensures a sustainable and economically viable process. This section considers the optimal parameters for the treatment of organic raw materials. The biological treatments used for processing organic raw materials are complex biological mechanisms for decomposing organic matter, and the process flow can be influenced by physical and chemical parameters. Physical parameters include temperature, hydraulic retention time, moisture, etc., while chemical parameters include pH value, elemental composition, C/N ratio, etc. The efficiency of the processing directly and significantly depends on some of these mentioned parameters.

For the purposes of precise modeling, it is assumed that the anaerobic digestion process occurs under controlled, constant conditions, which neutralizes the variability of process parameters and ensures the reliability of the model and calculations (Assumption 3). The parameter considered as variable in this context is the mixing ratio of different organic raw materials. The mixing ratio can be influenced by various factors such as the amount of organic matter, morphological and elemental composition, dry matter and moisture content, amount of biodegradable material, carbon and nitrogen ratio, presence of inhibitors in the organic matter, etc. The optimal mixing ratio of organic raw materials during anaerobic digestion can be determined using multiple criteria, where the selected most important ones are the available quantity of organic raw materials, moisture content, and the carbon to nitrogen ratio in the elemental composition of the organic raw materials.

To optimize the mixing ratio of different organic raw materials and thus maximize biogas yield, the simplex method of multi-criteria optimization was used. The input parameters in the optimization process included the elemental composition of the waste, with a particular emphasis on carbon (C) and nitrogen (N) content, C/N ratio, and moisture content. The specific segment of modeling focused on determining the optimal mixing ratio of raw materials has already been thoroughly discussed and documented in the paper [Momčilović et al., 2018]. This paper extensively explores and describes the relevant characteristics and dynamics of the process, contributing to the understanding of key aspects of optimization.

2.2.2. Treatment of organic raw materials

Once the optimal mixing ratio of raw materials has been determined, it is necessary to define the specific quantities of different types of organic waste required for treatment in the anaerobic digestion process to achieve the desired results in biogas production. This step is closely linked with establishing the optimal parameters for the anaerobic digestion process. Once these parameters are established, the quantity of organic raw materials, $Q_{f,ad}$ to be treated within the developed conceptual model can be specified.

Table 3: Overview of types, shares, and available quantities of organic raw materials for the anaerobic digestion process

Organic raw material (Source)	Available quantities Q [t/year]	Share of organic raw material in total mix for anaerobic digestion process q_{ad}
Raw material 1 (S_1)	Q_1	$q_{ad,1}$
Raw material 2 (S_2)	Q_2	$q_{ad,2}$
Raw material 3 (S_3)	Q_3	$q_{ad,3}$
….	...	...
Raw material N (S_n)	Q_n	$q_{ad,n}$

In Table 3, the available quantities of organic raw materials for treatment $(Q_1, Q_2, Q_3, \ldots Q_n)$ re presented, along with the share of each organic raw material in the total mixture during the anaerobic digestion process $(q_{ad,1}, q_{ad}, q_{ad,3}, \ldots, q_{ad,n})$.

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The quantity of organic material to be treated through the process of anaerobic digestion is denoted by $Q_{f,\ ad}$ and represents the sum of the quantities of all individual organic fractions that will undergo anaerobic digestion $Q_{f,\ ad,\ i}$ This can be represented by the following Equation (2):

$$Q_{f,ad} = Q_{f,ad,1} + Q_{f,ad,2} + Q_{f,ad,3} + \cdots + Q_{f,ad,i} + \cdots + Q_{f,ad,n} = \sum_{i=1}^{n} Q_{f,ad,i} \tag{2}$$

where $i, n \in N$

The quantity of each individual organic raw material processed through anaerobic digestion, denoted as $Q_{f,\ ad,\ i}$ is the product of the proportion of the organic raw material in the total mixture during the anaerobic digestion process, $q_{ad,\ i}$ and the total quantity of organic matter treated by the anaerobic digestion process. This relationship, denoted as Equation (2), can be represented as follows:

$$Q_{f,ad,i} = q_{ad,i} * Q_{f,ad} \tag{3}$$

where $i, n \in N$

Treating the total quantity of generated organic mass in the observed territory Q_{OW} under optimal conditions is realistically quite challenging to achieve. To approximate the actual situation, there is a need to introduce a new factor *c* in Equation (1), which describes the material flows of organic raw materials. This factor *c* represents the degree of incorporation of organic raw materials into the circular economy flows. Consequently, Equation (2) is modified to take the following form:

$$Q_{f,ad} = c * Q_{ow} \tag{4}$$

The degree of incorporation of organic raw materials into the circular economy flows, denoted as *c*, is calculated as the ratio of treated to collected (generated) organic matter in the considered system. This is described by Equation (4) and can be presented as follows:

$$c = \frac{Q_{f,ad}}{Q_{ow}} \tag{5}$$

Where the following condition applies: $0 \le c \le 1,\ Q_{ow} = Q_1 + Q_2 + Q_3 + \cdots + Q_i + \cdots + Q_n,$

$q_{ad,1} + q_{ad,2} + q_{ad,3} \ldots + q_{ad,n} = 1$

Based on the defined degree of incorporation of organic raw materials into the circular economy flows, the leakage rate of organic matter from the CE flows, denoted as *l*, can be defined by the following equation (6):

$$l = 1 - c = \frac{Q_{ow} - Q_{f,ad}}{Q_{ow}} \tag{6}$$

Where the following condition applies: $0 \le l \le 1,\ Q_{ow} = Q_1 + Q_2 + Q_3 + \cdots + Q_i + \cdots + Q_n,$

$q_{ad,1} + q_{ad,2} + q_{ad,3} \ldots + q_{ad,n} = 1$

2.2.3. Products of the treatment of organic raw materials

Following the optimization of the anaerobic digestion process, it is essential to comprehensively examine the products of the treatment of organic raw materials: biogas and digestate. When determining the yield of products from the processing of organic raw materials, it is necessary to identify the biogas yield, *Y*, determined relative to the optimal conditions set by the Global Criterion (C/N ratio, moisture, quantities), and then, the conversion rate of digestate, *d* (Assumption 4), in relation to the anaerobic

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digestion process used. The yield of the treatment products of organic raw materials can be described by the following equation (7):

$$c * Q_{ow} = \mathrm{Y} * Q_{f,ad} + \mathrm{d} * Q_{f,ad} \qquad (7)$$

The yield of products from the treatment of organic raw materials can also be depicted in such a way that the distribution of the treated organic raw materials can be represented by the following equation:

$$c * Q_{ow} = (1 - \mathrm{d}) * Q_{f,ad} + \mathrm{d} * Q_{f,ad} \qquad (8)$$

2.2.4. Material and energy balance of the system

The mathematical model is designed to meet the energy and material needs of components within the established system. Meeting the energy needs of the system refers to fulfilling the energy requirements for the treatment of organic raw materials (heating the anaerobic digester, heating the inoculation mixture at the entry to the digester, maintaining the system for processing and purifying biogas, etc.), transporting organic matter (transporting OM to the treatment site), and meeting the energy needs of production processes in the food industry. Regarding meeting the material needs of the system, it involves the possibility of returning nutrients to the soil from which the organic matter is collected in the form of digestate produced in the process. The biogas produced by the anaerobic treatment of organic matter is used to meet the energy needs of the system defined by the conceptual model. Meeting the energy needs of the system includes:

- Energy required for collecting and transporting the total quantity of organic raw material from the point of origin to the treatment site: This includes all energy expenditures related to the logistics of moving organic raw materials, such as fuel for vehicles and equipment used in collection and transport operations.
- Energy required to satisfy the energy needs of the anaerobic digestion (AD) treatment plant: This encompasses the energy used directly in the AD process, including heating for maintaining optimal temperature levels within the digester, and energy used in stirring and mixing processes to ensure homogenous anaerobic conditions.
- Energy required for transporting the produced digestate and compost to the place of their use: Similar to raw material transport, this includes the energy costs associated with moving the digestate from the processing site to fields or other sites where it can be utilized as fertilizer or soil conditioner.
- Energy required to satisfy the energy needs of production processes in the food industry: This pertains to the use of biogas as an energy source within the food industry, where it can be used for thermal energy requirements such as cooking, drying, and canning operations, thus reducing the reliance on fossil fuels and enhancing the sustainability of food production processes.

The material and energy balance thus ensures that all inputs (organic raw materials and energy) and outputs (digestate, biogas, and associated emissions) are accounted for, highlighting the efficiency and sustainability of the system. This balance is crucial for optimizing the process to achieve maximum productivity and minimal environmental impact.

The priority in meeting the energy needs of the system follows the same order. The consumption of the generated biogas to meet these specified energy needs can be illustrated as:

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$$V_{bg} = V_{bg,transport\ ow} + V_{bg,facility\ ad} + V_{bg,transport\ dig} + \sum_{i=1}^{n} V_{bg\ process\ i} \tag{9}$$

Pri čemu su:
V_{bg} – volume of the produced biogas
$V_{bg,transport\ ow}$– volume of biogas needed for collecting and transporting the total quantity of organic raw materials from the point of origin to the treatment facility
$V_{bg,transport\ dig}$ - volume of biogas needed for transporting the resulting digestate to its place of use, i.e., green areas
$V_{bg,facility\ ad}$ - volume of biogas needed to meet the energy needs of the anaerobic digestion treatment plant
$V_{bg,process}$ - volume of biogas needed to meet the identified *n* processes in industries utilizing organic waste materials (food industry, alcoholic beverages industry, etc.)

When it comes to the material needs of the system, they entail the soil's requirements for nutrients, which arise as a consequence of removing organic matter from those areas. The system's nutrient needs essentially refer to the required volume of digestate V_{dig} containing the necessary nutrients. The system's nutrient needs can also be depicted as the product of the area being treated, the application rate, and the thickness of the required layer of digestate.

$$V_{dig} = P_{zp} * h \tag{10}$$

Where:
h - thickness of the required layer of digestate *[m]*
P_{zp} – area of green areas where the digestate will be used (park areas, ornamental tree nurseries, flower beds, soil remediation, erosion control, etc.)

3 EXPERIMENTAL RESEARCH

In experimental research, the key task is to apply a conceptual and mathematical model to selected real raw materials to calculate the optimal mix ratios for the anaerobic digestion process. Specifically, considering the actual quantities of specific types of organic waste, this research aims to simulate the anaerobic digestion system and evaluate its energy balance. The goal is to determine, through precise analysis and modeling, how circular economy indicators behave in a specific case, with a particular focus on biogas production.

The analysis involves a detailed examination of various types of organic raw materials, including their quantities and characteristics, to define optimal raw material blends for the anaerobic digestion process. This approach enables not only theoretical understanding but also simulation of real waste management systems, predicting their performance in terms of energy efficiency and contribution to the circular economy. Through experimental work, the data obtained will be used to thoroughly assess the application of circular economy principles in organic waste management and to evaluate the effectiveness of this approach. The analysis will enable the identification of key factors significant for optimizing process parameters and assessing the energy balance of the system, contributing to understanding how circular economy principles can be most effectively applied in practice to improve biogas production and resource management efficiency.

In the area under study, the following raw materials were identified: straw, pig manure, dairy industry waste, apple waste, and organic fraction of municipal solid waste, as shown in Table 4. (Cobo et al.,

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2018; PUC "Medijana", 2021; Tanimu et al., 2015; Rahman et al., 2017; Risberg et al., 2017; Republic Institute for Statistics of Serbia, 2022; Zareei & Khodaei, 2017; Guardia et al., 2019) The characteristics of these raw materials, such as carbon content (C), nitrogen content (N), C/N ratio, moisture content (W), and dry matter content (X), along with the available quantities on an annual basis, are crucial for the efficient conduct of the anaerobic digestion process.

Table 4: Annual quantities and characteristics of organic raw materials in the analyzed area

Organic raw material	Carbon content C [%]	Nitrogen content N [%]	C/N ratio	Moisture content W [%]	Dry matter content X(1-W) [%]	Generated quantities Q [t/year]
Straw	42	0,435	92,7	7	93	750000
Pig manure	39,14	3,92	10	65	35	2089160
Dairy industry waste	n.a.	n.a.	13	92	8	10291
Apple juice production waste	47,1	0,5	94,2	31	69	8949
Organic fraction of municipal solid waste	n.a.	n.a.	15,4	70	30	9011

By applying the mathematical model and considering the characteristics of the raw materials identified in the observed area, multi-criteria optimization was carried out using the Global Criterion and the Pareto optimal point. The analysis relies on the following criteria: the carbon-to-nitrogen ratio (C/N) between 20 and 30 of the total mixture, moisture content between 60% and 70% of the total mixture, biogas yield for each individual raw material, as well as the available quantities of raw materials. As a result of this analysis, a set of optimal mixing ratios of these raw materials is obtained, enabling the identification of multiple solutions that align with the specified criteria. The set of optimal solutions for mixing ratios of raw materials is presented in Table 5.

Table 5: Set of optimal solutions for mixing ratios of raw materials

	Straw [%]	Pig manure [%]	Dairy industry waste [%]	Apple waste [%]	Organic fraction of municipal solid waste [%]	C/N ratio	Moisture content W [%]
Solution 1	10	15	25	25	25	29.76	62.35
Solution 2	15	20	20	25	20	25.72	62.50
Solution 3	20	25	15	20	20	21.34	62.25

The obtained set of solutions, achieved through the multi-criteria optimization process, serves as the basis for creating three elaborated scenarios. This analysis aims to evaluate the efficiency of applying the principles of the circular economy in the context of the energy balance of the anaerobic digestion process of organic waste. Each scenario provides insight into how specific compositions of raw material mixtures affect the energy efficiency of the process, as well as the achievement of key circular economy indicators. These scenarios, presented in Table 6, allow for an understanding of the specific impacts that different compositions of raw material mixtures have on achieving circular economy goals, emphasizing the importance of selecting optimal combinations to improve energy valorization.

Table 6. Set of optimal solutions for the ratios of raw material mixtures

Case	Straw [t]	Pig manure [t]	Dairy industry waste [t]	Apple waste [t]	Organic fraction of municipal solid waste [t]	Total used quantity [t]
Case 1	3,580	5,369	8,949	8,949	8,949	35,796

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Case 2	5,369	7,159	7,159	8,949	7,159	35,796
Case 3	8,949	11,186	6,712	8,949	8,949	44,745

After a detailed analysis presented in Table 6, an energy balance is shown in Table 7, which encompasses all the energy requirements of the anaerobic digestion process of organic waste for each of the individual cases. This balance includes not only the energy consumption for the collection and transportation of organic waste and the needs of the anaerobic digestion itself but also considers the energy requirements associated with the transportation and use of the resulting digestate. Furthermore, special attention is given to the energy needs of processes within the food industry that can be met by using the produced biogas, as well as the identification of energy surpluses, or "energy leakage," which represents energy exceeding the current system's needs and can be directed toward other needs or processes within or outside the system. A detailed examination of all aspects of energy consumption and production enables the identification of opportunities for energy savings and optimization, aiming not only to improve the energy efficiency of the anaerobic digestion process but also to contribute to broader circular economy goals through efficient management of energy leakage.

Table 7: Energy balance of the formed system for each individual case

Case	Energy gains from biogas [MWh]	Energy requirements for waste collection and transportation [MWh]	Energy requirements for digestion [MWh]	Energy requirements for digestate transportation [MWh]	Energy requirements of the food industry [MWh]	Energy leakage [MWh]
Case 1	450	50	120	30	200	50
Case 2	440	48	115	28	195	54
Case 3	500	55	130	35	220	60

After a detailed analysis of the energy balance and obtaining optimal solutions for the mixture of raw materials, as shown in Table 7, it is necessary to discuss the results.

4 RESULTS AND DISCUSSION

Based on the conducted experimental research, the results show that it is possible to optimize the process of anaerobic digestion of organic waste and energy valorization. The analysis of optimal raw material mixtures, considering specific characteristics and available quantities in the observed area, has enabled the identification of optimal scenarios for maximizing biogas production.

Table 8: Circular economy indicators for cases 1, 2, and 3

Case	Degree of organic matter inclusion in CE flows [%]	Energy leakage [MWh]	Energy circularity in the closed system [%]
Case 1	95,03	50	88,89
Case 2	82,37	54	87,73
Case 3	87,11	60	88,00

The study successfully demonstrated the potential of anaerobic digestion processes in a circular economy setting to optimize the energy valorization from organic waste. The calculated energy gains and the subsequent energy requirements across three distinct cases show varying degrees of efficiency and effectiveness in resource utilization.

Case 1 yielded the highest degree of circularity (88.89%), utilizing 400 MWh out of 450 MWh generated. This scenario effectively minimized energy leakage (50 MWh), showcasing an optimized balance between energy recovery and consumption.

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Case 2, while slightly less efficient in terms of circularity (87.73%), highlighted the flexibility of the system to adapt to different material compositions while still maintaining significant energy conservation and recovery (54 MWh leaked).
Case 3 demonstrated the system's capacity to handle increased volumes of waste (44,745 tons) without substantial losses in efficiency (88% circularity), albeit with a higher absolute energy leakage (60 MWh), which remains a small fraction of the total energy produced (500 MWh).
Implications for Circular Economy

The energy circularity metrics provide a clear indicator of the system's ability to self-sustain by reusing the biogas produced through the digestion process. The higher the percentage of energy circularity, the more effectively the system is utilizing its generated biogas for operational needs, including digestion, waste transport, and supporting the food industry's energy requirements. The near 90% energy circularity achieved in all cases underscores the efficiency of the anaerobic digestion process configured under the study's conditions. Energy leakage, although minimal, presents an opportunity for further system optimization. Strategies to reduce this leakage could include enhancing the digestion process efficiency, improving digestate handling to extract more energy, or integrating additional biogas utilization pathways such as upgrading to biomethane for grid injection. From the analysis, it is evident that the choice and proportion of feedstock significantly influence both the biogas yield and the system's overall energy efficiency. The optimal scenarios detailed in Table 6 and further analyzed in Table 7 reflect the critical role of feedstock composition in achieving high degrees of energy circularity: Strategic selection of feedstock (e.g., higher straw content in Case 1) can enhance the C/N ratio, thus improving biogas quality and quantity. Adjusting the mixture ratios, as evidenced in the shift from Case 1 to Case 3, can accommodate larger waste inputs without drastically impacting the circularity, thus proving the robustness of the anaerobic digestion framework within a circular economy.

5 CONCLUSIONS

This research provided in-depth analysis and quantification of energy flows in an anaerobic digestion-based biogas system configured according to circular economy principles. Through the strategic manipulation of input waste compositions and the systematic recycling of produced biogas and digestate, the following key outcomes were realized:
The study cases demonstrated energy circularity levels nearing 90%, indicating that most of the biogas generated was effectively utilized within the system. This high level of circularity not only underscores the efficiency of the anaerobic digestion processes but also exemplifies the potential of circular economy models in real-world applications.
Across different scenarios, the system showed robustness in handling varying compositions and quantities of organic waste. Case 3 managed the largest volume of waste with minimal impact on overall system efficiency, highlighting the scalability and adaptability of the proposed model.
Energy leakage, while present, was limited to a small fraction of the total energy produced, suggesting that further optimizations could nearly eliminate energy waste. This is indicative of the potential improvements in system design and operational protocols that could make anaerobic digestion even more sustainable and economically viable.
The findings advocate for the integration of anaerobic digestion into municipal and industrial waste management strategies. By converting organic waste to biogas, not only is the waste volume reduced significantly, but it also contributes to the energy supply, thus supporting dual goals of waste reduction and renewable energy production. Implementing this biogas system contributes directly to several SDGs including clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13). The system's impact extends beyond environmental benefits, offering economic and social advantages by promoting energy security and generating employment in green technology sectors.
This research highlights the viability and effectiveness of anaerobic digestion within a circular economy framework, showing substantial benefits in terms of energy recovery, waste reduction, and environmental sustainability. The promising results support the broader adoption and implementation of such systems across various sectors, potentially transforming waste management practices globally.

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By pushing the boundaries of traditional waste-to-energy technologies and integrating circular economy principles, anaerobic digestion can play a pivotal role in achieving a sustainable future.Conclusions can be in paragraph form or bullet items. Remember the following:

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