

Retrofitting Digestate Recirculation System to Improve Methane Yield in Anaerobic Digestion

Elang Nur Reiz M N Insaani*, Hafif Dafiqurrohman, Adi Surjosatyo, Cindy Rianti Priadi, Baskoro Lokahita

Universitas Indonesia

Email: elangnurreizmninsaani@gmail.com*, hafif.dafiqurrohman@ui.ac.id,
adisur@eng.ui.ac.id, crpriadi@eng.ui.ac.id, baskoro.lokahita@ui.ac.id

Keyword:

Food waste; Recirculated Digestate; Modelling; Anaerobic Digestion; Methane

Abstract

Digestate recirculation has gained attention as a promising strategy to enhance methane production. By reintroducing acclimatized microorganisms and residual biodegradable compounds into Anaerobic digestion (AD) system, this approach can potentially improve process stability and biogas quality. To systematically evaluate these effects, modeling and simulation offer a reliable framework for assessing methane yield. This study aims to assess the feasibility of simulating methane production from an anaerobic digestion reactor using food waste (FW) as the primary feedstock, incorporating a digestate recirculation system. It is hypothesized that recirculated digestate, due to its high organic content and catalytic properties, can effectively enhance biogas quality and optimize energy recovery from the system. A process flow diagram was developed in Aspen Plus® version, incorporating the four main biochemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The Non-Random Two-Liquid (NRTL) thermodynamic model was applied to represent polar mixture components, and a total of 46 governing equations were implemented to describe anaerobic digestion kinetics and mass balances. Model performance was validated against data reported in previous studies. Simulation results indicate that increasing the recirculation ratio up to 30% into feedstock mixture enhances both methane up to 25% higher compared to baseline and biogas production up to 32% higher than baseline. The findings demonstrate that the usage of recirculated digestate could improve the biogas quality. The developed modeling framework shows strong potential for scalability and can be applied to optimize methane production in anaerobic digestion systems with similar feedstock compositions and operating conditions.

INTRODUCTION

Renewable energy has become increasingly important as global energy demand rises, and environmental concerns intensify due to continued reliance on fossil fuels. Organic waste represents a promising source of renewable energy because it could be converted into useful energy through processes such as anaerobic digestion, while simultaneously helping to reduce environmental pollution. Although waste materials are often regarded as having low economic value and may pose environmental challenges, from an energy recovery perspective, the methane produced from waste through anaerobic digestion represents a valuable renewable energy source. Methane, the main combustible component of biogas, possesses significant energy potential due to its high calorific value. Khanal, (2008) reported that the net heating value of methane is approximately 37,750 kJ/m³. According to (Weiland, 2010), biogas is expected to play a major role as a future energy source due to its constant availability, low cost, and versatility. It can be utilized for activities ranging from cooking and electricity generation to hydrogen or steam production, as well as fuel for transportation.

Southeast Asia assessing the Anaerobic digestion has emerged as a promising technology for transforming waste into clean energy. Its advantages include efficient removal of biodegradable organic matter, flexibility for implementation across different scales and locations, and the generation of well-stabilized excess sludge in minimal amount. And most of all, the key advantage of anaerobic process is the positive net energy production, mainly as biogas and to a lesser extent as microbial heat. Anaerobic digestion (AD) is a biochemical process in which complex organic materials are decomposed by microorganisms in the absence of oxygen. Resulting primarily in the production of biogas and digestate. The degradation of organic matter occurs through four sequential stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex polymers such as carbohydrates, proteins, and lipids are broken down into simpler monomers, namely sugars, amino acids, and fatty acids, by extracellular enzymes produced by facultative anaerobic microorganisms. These monomers are subsequently converted into volatile fatty acids (VFAs) during the acidogenesis stage. In acetogenesis, VFAs are further transformed into acetic acid, hydrogen, and carbon dioxide. Finally, methanogenic archaea convert acetic acid, hydrogen, and carbon dioxide into methane and carbon dioxide during the methanogenesis stage.

The performance of anaerobic digestion processes is influenced by several factors, including reactor type, temperature, residence time, and feed concentration, and its been continually studied for past decades. Wilson et al., (2008) investigated the effects of reaction temperature on the process performance and operational stability, demonstrating that operation beyond optimal temperature can lead to the accumulation of volatile fatty acids and gaseous hydrogen, which corresponded with low observed methane output. More recently, (Yang et al., 2024) examine the optimum process performance by balancing both hydraulic retention time (HRT) and organic loading rate (OLR) parameters, highlighting the importance of their coupled interaction in maximizing methane yield and maintaining system stability. The choice of substrate is also one of the key factors in determining the quality of biogas produced in anaerobic digestion systems. (Qian et al., 2025) compared the effects of different feedstock materials on anaerobic digestion performance, as well as the effectiveness of various enhancement methods.

In addition to biogas, anaerobic digestion produces digestate, which is commonly utilized as a biofertilizer (Jankauskienė et al., 2024) or disposed of in landfills. However, digestate is not merely a residual waste product. According to (Möller, 2015), digestate is a complex matrix consisting of partially degraded organic matter, inorganic compounds, and active microbial biomass. This composition suggests that digestate retains biodegradable potential and can be reused as a substrate for further biogas production through anaerobic digestion. Digestate recirculation may enhance substrate utilization, stabilize microbial communities, and potentially increase methane yields. Despite this promising potential, research focusing on the reuse of digestate as a feedstock in anaerobic digestion systems remains relatively limited, highlighting an important research gap.

The study of anaerobic digestion optimization has become an increasingly prominent research topic, driven by the need to achieve optimal biogas composition through careful assessment of suitable substrate characteristics and operational parameters, including temperature, pressure, feedstock ratio, and residence time. However, given the high cost and time demands of experiment-based research, modeling approaches are progressively being

used as efficient alternatives for analyzing parameter interactions. To better understand and evaluate the complex biochemical processes involved in such integrated systems, modeling and simulation tools play a crucial role. One of the most widely recognized frameworks for anaerobic digestion is the Anaerobic Digestion Model No. 1 (ADM1), which describes the biological and chemical processes occurring during digestion.

Numerous studies have reported on the successful application of ADM1-based approaches in improving biogas production from anaerobic digestion systems. For instance, Rosén & Jeppsson, (2005) demonstrated systematic ADM1 implementation, calibration, and benchmarking (BSM2), improving reliability and enabling standardized performance evaluation of AD systems. (Vaneckhaute et al., 2018) integrated ADM1-based modeling with monitoring strategies, enhancing dynamic simulation and enabling improved process control and operational stability. Subsequently, (García-Diéguez et al., 2013) developed a reduced-order ADM1 suitable for control and optimization applications, facilitating industrial implementation and real-time predictive use. In parallel, (Bonk et al., 2018) extended ADM1 to better represent ammonia inhibition dynamics, improving predictive capability for high-nitrogen substrates and co-digestion systems. Collectively, these findings suggest that statistical and metaheuristic techniques can enhance anaerobic digestion performance while minimizing dependence on labor-intensive experimental studies.

Modeling approaches are often adapted to specific operational conditions, as anaerobic digestion performance can vary significantly depending on feedstock composition, reactor configuration, and environmental parameters. Simulation tools allow researchers and engineers to assess system feasibility prior to full-scale implementation, analyze the performance of existing systems, and optimize design and operational strategies for improved efficiency. Aspen Plus® has been extensively used and validated as a process simulation platform across numerous studies on anaerobic digestion system. For instance, (Rajendran et al., 2014) utilized Aspen Plus to develop an integrated Process Simulation Model (PSM) representing the sequential biochemical stages of anaerobic digestion through comprehensive mass and energy balances, while (Aguilar et al., 2017) applied the software to simulate anaerobic co-digestion of food waste and primary sludge integrated with a combined heat and power (CHP) system to evaluate overall energy recovery efficiency. Additionally, (Bhatt & Tao, 2020) employed Aspen Plus to assess the techno-economic feasibility of biogas production from anaerobic digestion. Process parameter investigations by (Anaya Menacho et al., 2022) and (Adesiyan et al., 2024) further demonstrated its capability to analyze the influence of operational variables such as hydraulic retention time (HRT), organic loading rate (OLR), and temperature on biogas yield and composition. Expanding the modeling scope, (Budhraj, 2024) used Aspen Plus to simulate and optimize both methane and biohydrogen production potentials from various organic wastes, while (Mihi et al., 2024) proposed a modified dynamic mathematical model integrated within Aspen Plus to simulate the coupled biochemical and physicochemical processes involved in anaerobic digestion, thereby enhancing the dynamic representation and predictive accuracy of biogas production systems.

Although various approaches have been developed in anaerobic digestion system, comprehensive studies that simultaneously examine the influence of substrate characteristics, estimate biogas production through anaerobic digestion with digestate recirculation system, are still very limited. To the best of our knowledge, no prior research has comprehensively

analyzed anaerobic digestion with recirculation system within a single framework to evaluate its biogas production. Accordingly, this study investigates biogas production from anaerobic digestion systems with digestate recirculation through simulation-based modeling. Feedstock ratio and flow rate are selected as key input parameters, while biogas yield, methane yield, and biogas composition serve as the principal performance metrics. The system utilizes food waste as the primary feedstock, supplemented with and recirculated digestate.

Based on the identified research gap, this study aims to develop a comprehensive Aspen Plus simulation model of anaerobic digestion with digestate recirculation, evaluate the effect of recirculation ratios (0–90%) on methane yield, biogas production, and composition, determine the optimal ratio that maximizes methane while maintaining stability, analyze macronutrient concentration changes, and assess biogas quality. Theoretically, this research enriches anaerobic digestion modeling by integrating digestate recirculation into the ADM1-based framework, offering insights into substrate composition and gas production pathways. Practically, it provides biogas plant operators and policymakers with an optimal recirculation ratio (30%) as an operational guideline, and the simulation framework can be adapted for other organic wastes, supporting sustainable waste-to-energy technologies and circular economy principles.

METHOD

This research employed a quantitative simulation-based approach to evaluate the effect of digestate recirculation on methane production and its potential conversion into electrical energy. No experimental work was conducted in this study. Instead, substrate characteristics of food waste were obtained from previous experimental studies, while reaction pathways and kinetic parameters were adopted from (Rajendran et al., 2014). All collected datasets were structured as input parameters for simulation, enabling the development of a representative anaerobic digestion model.

Process simulation was performed using Aspen Plus version 12 to model both the anaerobic digestion system processes. The model was developed based on fundamental mass and energy balances, allowing prediction of system behavior under steady-state conditions. The overall system consisted of three main stages: anaerobic digestion for biogas production, gas purification to improve methane quality, and energy conversion using a gas-based power system. Key assumptions included constant substrate characteristics, steady-state operation, and fixed kinetic parameters across all simulation scenarios. Thermodynamic properties were defined using the Non-Random Two-Liquid (NRTL) model to represent phase interactions in multicomponent systems.

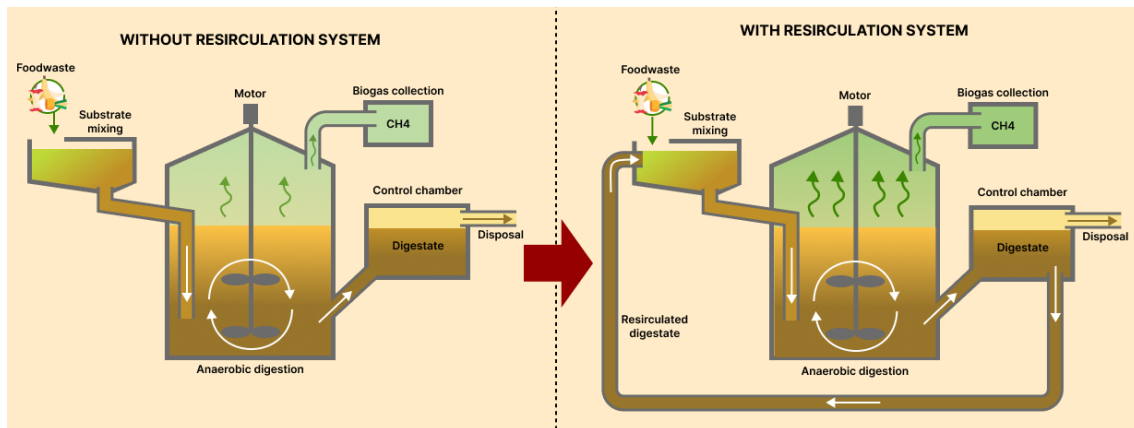


Figure 1. Retrofitting of anaerobic digestion process using recirculation system illustration
 Source: Authors' conceptual diagram (2024)

The anaerobic digestion process was modeled based on Anaerobic Digestion Model No. 1 (ADM1) (Batstone et al., 2002), which describes the biochemical conversion of organic matter into methane and carbon dioxide through sequential stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The model incorporates both biochemical reactions and physicochemical processes such as gas–liquid transfer and acid base equilibria, enabling a comprehensive representation of digestion dynamics. In this study, hydrolysis reactions were modeled using stoichiometric conversion, while subsequent stages were simulated using kinetic-based reactions within a continuous stirred tank reactor (CSTR). A total of 46 reactions were included, with kinetic parameters obtained from literature sources and assumed constant for all cases.

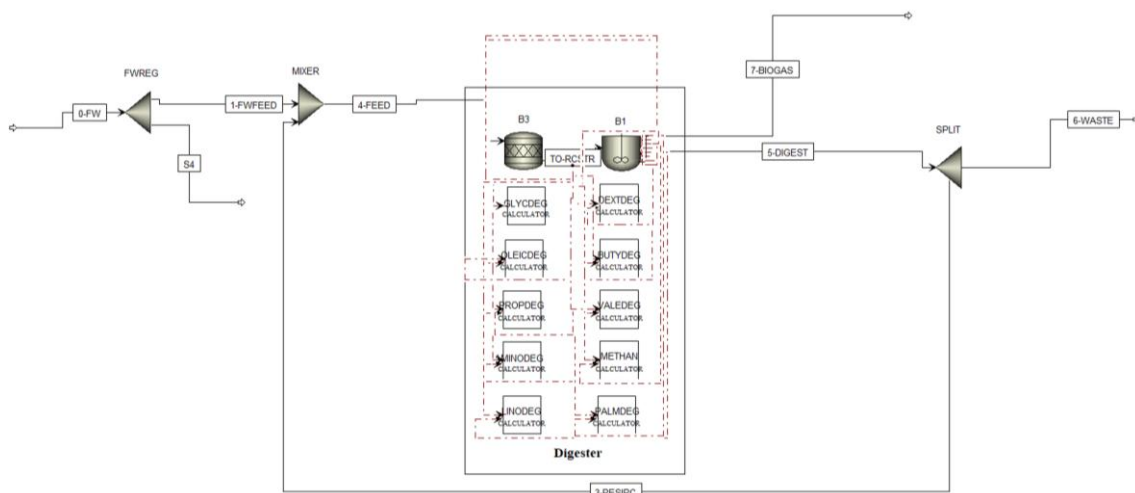


Figure 2. Process flow diagram of anaerobic digestion model with recirculation system
 Source: Authors' Aspen Plus simulation flowsheet (2024)

Previous studies, such as Appels et al., (2008) reported that the anaerobic digestion of proteins and carbohydrates generally produces biogas containing approximately 50–58% methane, whereas lipid-rich substrates tend to generate biogas with higher methane concentrations, typically ranging from 66% to 73%. These differences highlight the importance of substrate composition in determining biogas quality and yield. Therefore, a comprehensive

characterization of carbohydrate, protein, and lipid fractions is essential for accurately predicting anaerobic digestion performance. The summarized substrate characteristics compiled from several literature sources are used in this study as representative feedstock inputs for the anaerobic digestion reactor modelling.

To assess the impact of digestate recirculation, a series of simulation scenarios were developed using a mixture design approach. Substrate composition ratios between food waste and recirculated digestate varied systematically, resulting in multiple scenarios under a fixed daily feeding rate. Model outputs, including methane yield, biogas production, and gas composition, were analyzed comparatively to identify optimal conditions for methane generation. The system was operated under thermophilic conditions to enhance microbial activity and reaction rates.

Table 1. Simulation scenarios based on substrate compositions

No	Component 1: Food waste		Component 2: Recirculated digestate	
	%	kg	%	kg
1	100	150	0	0
2	90	135	10	15
3	80	120	20	30
4	70	105	30	45
5	60	90	40	60
6	50	75	50	75
7	40	60	60	90
8	30	45	70	105
9	20	30	80	120
10	10	15	90	135

Source: Authors' simulation design (2024)

Model validation was conducted through comparison with published data from previous studies. Simulated results were evaluated against reported ranges of methane yield, biogas composition, and system performance to ensure consistency and reliability. This approach allows the model to provide a realistic representation of anaerobic digestion behavior and supports its application for process optimization and energy recovery analysis.

RESULTS AND DISCUSSION

Substrate Characteristics

Three major groups of organic compounds with high biogas yield potential were analyzed in the substrate characterization, namely carbohydrates, proteins, and lipids. These components represent the principal biodegradable fractions in organic waste and play a critical role in determining methane yield and overall anaerobic digestion performance. In this study, carbohydrates were represented by cellulose, starch, and hemicellulose, which are commonly found in food waste and lignocellulosic residues. Carbohydrates are among the most abundant organic compounds on Earth and serve as a primary energy source. They are generally classified into monosaccharides, oligosaccharides, and polysaccharides. However, for stoichiometric simplification in this study, their hydrolysis products were represented by a single monosaccharide, dextrose (D-glucose). Cellulose is a strong structural polymer in plant

tissues and is relatively resistant to biodegradation, which can influence the hydrolysis rate during anaerobic digestion.

Proteins were classified based on their solubility into soluble and insoluble proteins, as solubility significantly affects hydrolysis kinetics and biodegradability. Amino acids, the building blocks of proteins, exhibit diverse physicochemical properties. They can be categorized nutritionally into essential amino acids (e.g., valine, leucine, isoleucine, phenylalanine, tryptophan, methionine, threonine, histidine, lysine, and arginine) and nonessential amino acids (e.g., glycine, alanine, proline, serine, cysteine, tyrosine, asparagine, glutamine, aspartic acid, and glutamic acid). Some amino acids such as proline, hydroxyproline, glycine, and alanine are relatively soluble, while others like cystine and tyrosine show lower solubility, which can affect their degradation behaviours in anaerobic systems.

Lipids were represented by tripalmitate, triolein, palmito-olein, and palmitolinolein. Lipids are insoluble in water but soluble in organic solvents, a property that facilitates their separation from proteins and carbohydrates during analysis. In biological storage tissues, lipid content can reach 15–20% or higher, making them an important energy-rich substrate. Although lipids typically degrade more slowly than carbohydrates, they possess higher theoretical methane potential due to their elevated carbon and hydrogen content.

Food waste characteristics

Food waste (FW) is widely recognized as a suitable substrate for anaerobic digestion due to its high organic content, biodegradability, and moisture level. It has been reported to produce biogas yields of up to 0.6 m³/kgVS with methane content of 70–80%, indicating strong potential for renewable energy generation. However, the composition of FW is inherently heterogeneous, varying depending on its source, seasonal availability, and dietary patterns.

To obtain representative input data for this study, a meta-analysis was conducted based on multiple literature sources, as summarized in **Table 2. Food waste characteristics**. The analysis shows that FW is predominantly composed of water, with an average content of 74.17 % ww, making it suitable for wet anaerobic digestion systems. In terms of organic composition, carbohydrates dominate at 11.96 % ww, followed by lipids at 5.17 % ww and proteins at 3.94 % ww. This distribution suggests that FW contains a high fraction of readily biodegradable compounds, which supports rapid hydrolysis and acidogenesis, while lipids contribute to higher methane potential despite their lower proportion.

Table 2. Food waste characteristics

No.	Carbohydrate (%ww)	Protein (%ww)	Lipid (%ww)	Water content (%ww)	Source
1	4.68	2.64	3.84	88.00	(Ekstrand et al., 2022)
2	7.22	4.21	3.01	77.20	(Fisgativa et al., 2016)
3	-	0.00	0.00	72.60	(Mohammadianroshanfekr et al., 2024)
4	11.67	4.12	3.97	74.90	(Moonsamy et al., 2024)
5	-	3.36	6.14	80.84	(Lopez et al., 2016)
6	15.18	2.68	2.19	79.20	(Pagliaccia et al., 2019)
7	6.83	3.34	1.91	77.00	(Poe et al., 2020)
8	14.95	3.63	3.61	76.50	(Ariunbaatar et al., 2015)
9	17.35	5.32	5.12	70.60	(Browne & Murphy, 2013)

No.	Carbohydrate (%ww)	Protein (%ww)	Lipid (%ww)	Water content (%ww)	Source
10	7.60	1.99	1.19	80.40	(Han et al., 2015)
11	-	3.33	3.92	65.00	(Kiran & Trzcinski, 2017)
12	9.34	8.26	1.47	77.60	(Liu et al., 2016)
13	11.62	4.76	4.99	77.00	(Selvam et al., 2021)
14	2.37	1.29	0.49	90.49	(Shen et al., 2013)
15	1.94	3.32	6.53	77.39	(Shen et al., 2013)
16	28.31	7.76	14.38	47.50	(Slopiecka et al., 2022)
17	5.20	0.93	0.00	91.00	(Song et al., 2023)
18	18.59	7.82	30.23	43.35	(Xue et al., 2020)
19	28.22	7.06	3.92	60.00	(Yan et al., 2016)
20	12.28	2.93	6.49	76.80	(Zhang et al., 2018)
Average	11.96	3.94	5.17	74.17	

Source: Compiled from literature

The averaged values obtained from this meta-analysis are used as the basis for defining the substrate composition in the simulation model. This approach ensures that the input data reflects a realistic and representative characterization of food waste, while also accounting for variability reported across different studies. By incorporating these averaged parameters, the model is able to simulate anaerobic digestion performance under conditions that are consistent with typical FW characteristics observed in practical applications.

Digestate characteristics

As part of the input configuration for the digestate stream prior to simulation, only the recirculation ratio or volume of digestate is predefined. The physicochemical characteristics of the digestate, including its composition and nutrient concentrations, are not specified a priori but are instead generated dynamically from the simulation results. Consequently, the properties of both the produced and recirculated digestate are inherently determined by the system behaviour under each scenario.

The resulting digestate characteristics are presented in **Figure 3**, which illustrates the distribution of macronutrients within the system. In this representation, carbohydrates, proteins, and lipids are expressed as aggregated categories. Each category encompasses not only the original substrate components but also their respective intermediate and degradation products formed throughout the anaerobic digestion process, including hydrolysis, acidogenesis, and acetogenesis. This lumped approach is adopted to simplify the interpretation of complex biochemical pathways while still capturing the overall transformation and accumulation of organic matter within the system.

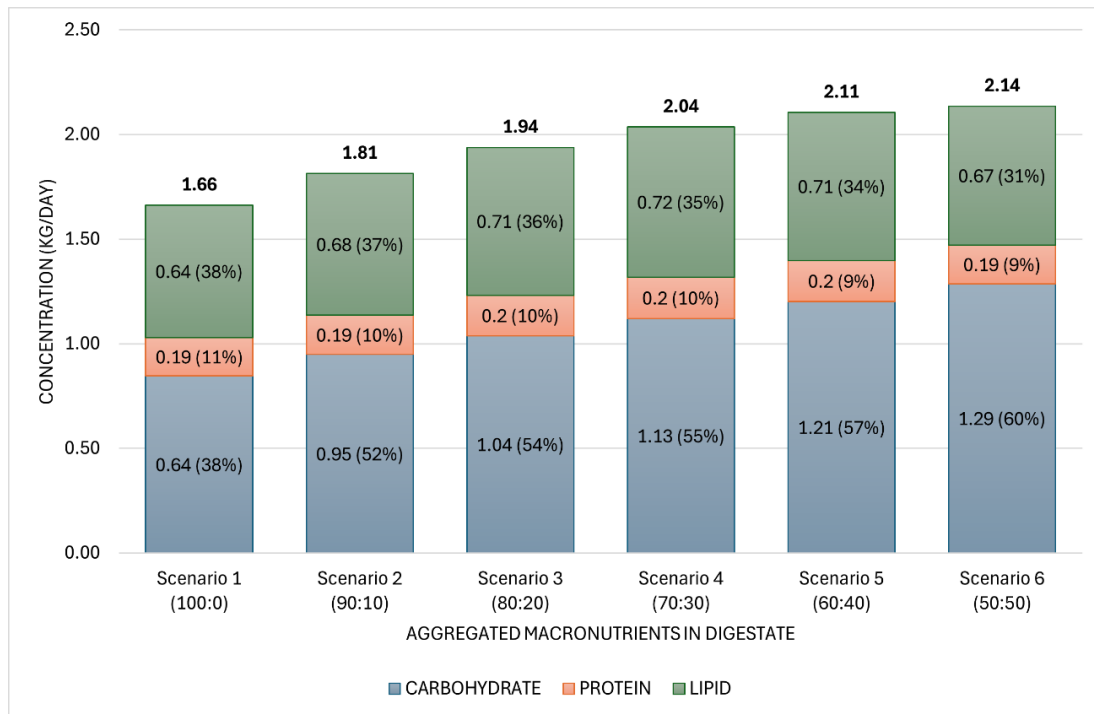


Figure 3. Digestate Macronutrients Concentration in kg/day. Macronutrients categories (carbohydrates, proteins, and lipids) represent aggregated components, including both primary substrates and their intermediate degradation products formed across anaerobic digestion stage

Source: Authors' simulation results (2024)

Despite maintaining a constant volumetric flowrate across all scenarios, the simulation indicates an increase in the total amount of digestate produced with increasing recirculation ratios. The macronutrient composition is predominantly composed of carbohydrates (approximately 38–60%), followed by lipids (31–38%), and a smaller fraction of proteins (9–11%). This distribution reflects the differing biodegradability and conversion pathways of each macronutrient, where carbohydrates tend to persist as intermediate compounds, while proteins and lipids undergo more extensive degradation.

The use of digestate as a recirculated substrate is supported by previous studies, which have demonstrated its potential to enhance methane production. In particular, the integration of residual organic matter and active microbial communities in digestate can improve process performance. Previous research has demonstrated that the biomethane output may be greatly increased by anaerobic co-digestion of waste-activated sludge (WAS) with lipid-rich waste (Beale et al., 2016; Salama et al., 2019; Wang et al., 2013).

Increased macro nutrient content of mixed substrate

The simulation results provide a detailed representation of substrate nutrient characteristics by quantifying the concentration of individual reactant compounds associated with each stage of the anaerobic digestion process. Specifically, the model captures the transformation of macro-nutrients: carbohydrates, proteins, and lipids, through the key biochemical phases of hydrolysis, acidogenesis, acetogenesis and methanogenesis. Each phase is represented by its corresponding intermediate compounds, such as simple sugars from carbohydrate breakdown, amino acids from protein degradation, and fatty acids from lipid

conversion. By tracking these components across different recirculation ratios, the simulation enables a comprehensive analysis of how digestate recirculation influences the distribution and conversion of organic matter within the system.

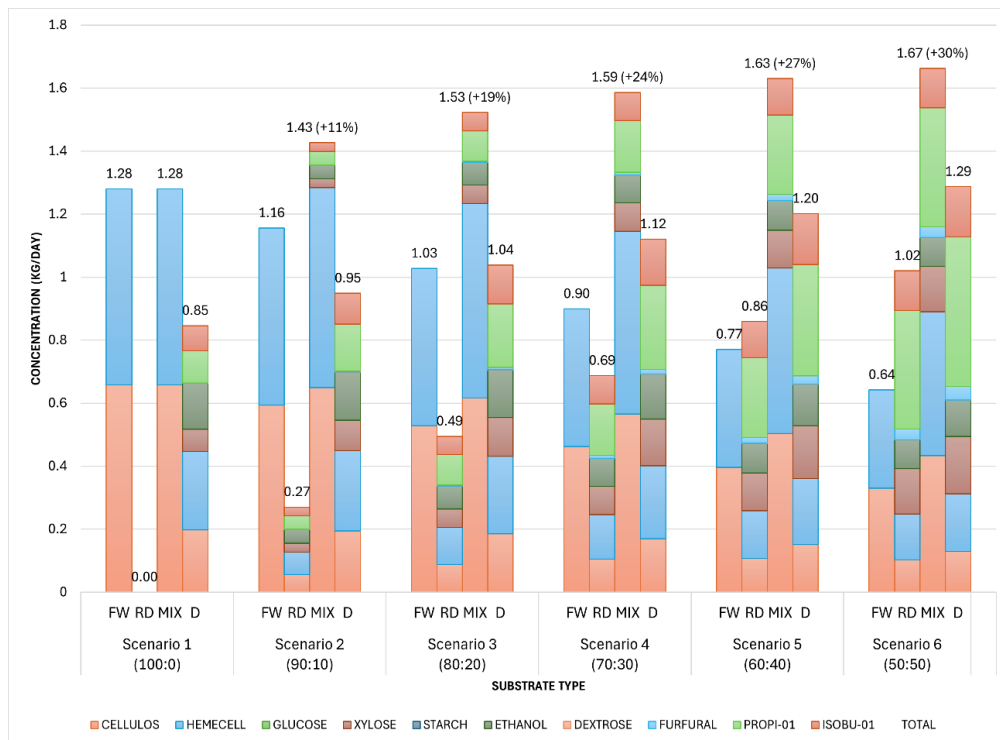


Figure 4. Effect of different recirculation ratio on carbohydrate concentration (kg/day) in Food Waste (FW), Recirculated Digestate (RD), Mixture Substrate (MIX), and Digestate (D)
Source: Authors' simulation results (2024)

The results as shown in **Figure 4** indicate that the carbohydrate concentration in the digestate remains relatively high, even after the anaerobic digestion process. This suggests that a fraction of carbohydrates is not fully degraded and persists in the digestate, making it a potential source of organic matter when recirculated.

With the addition of recirculated digestate (RD) at increasing ratios, the carbohydrate concentration in the resulting mixture (MIX) also consistently increases significantly from 11% at 10% recirculation ratio (Scenario 2), up to 30% at 50% recirculation ratio (Scenario 6). This occurs because the digestate itself already contains high residual carbohydrate compounds, which are then reintroduced into the system along with the fresh food waste. As the proportion of RD increases, its contribution to the overall feed composition becomes more significant, leading to a cumulative increase in total carbohydrate concentration in the mixture.

Overall, the addition of RD enhances the carbohydrate concentration in the mixture digestate. This indicates that recirculation not only acts as a means of microbial and nutrient recycling but also reintroduces partially degraded organic compounds, thereby increasing the overall carbohydrate load entering the system.

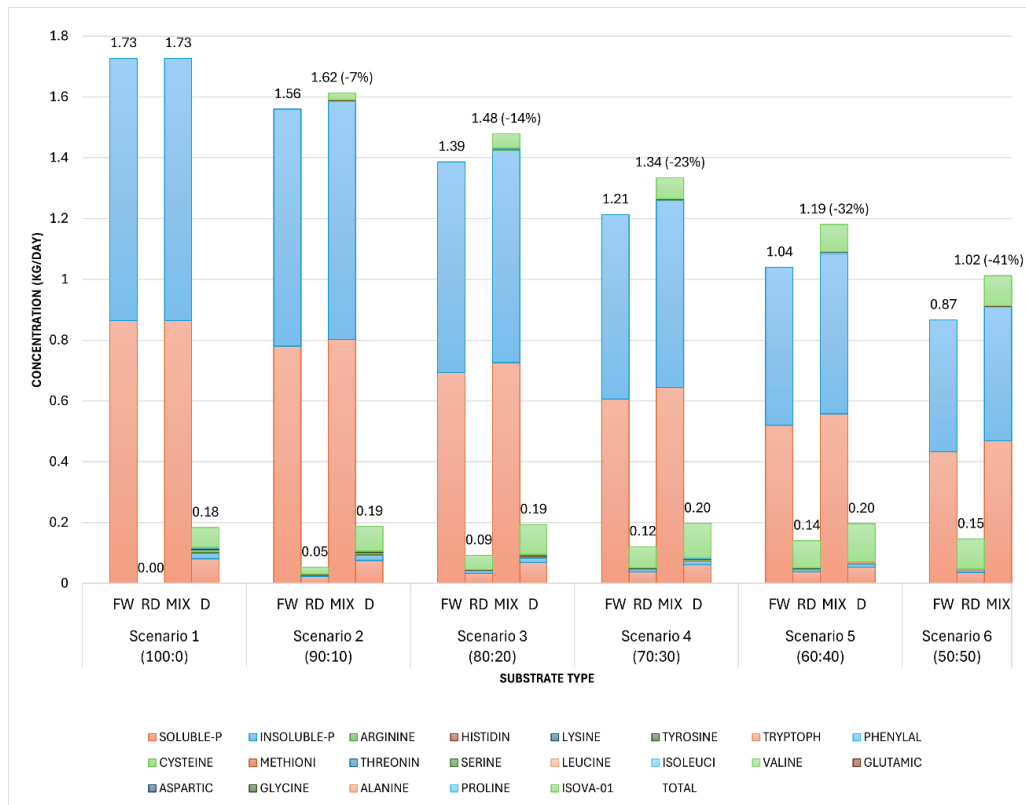


Figure 5. Effect of different recirculation ratio on protein concentration (kg/day) in Food Waste (FW), Recirculated Digestate (RD), Mixture Substrate (MIX), and Digestate (D)
Source: Authors' simulation results (2024)

The protein concentration became very low after anaerobic digestion process, indicating almost complete degradation of the protein fraction. Consequently, soluble protein (SOLUBLE-P) and insoluble protein (INSOLUBLE-P) as macromolecular protein compounds remained the dominant components, with higher concentrations than their degradation products. In contrast to carbohydrates, the concentration of protein in the system shows a decreasing trend with the addition of recirculated digestate (RD), declining from 7% at 10% recirculation ratio (Scenario 2) to 41% at 50% recirculation ratio (Scenario 6) as shown in **Figure 5**. Although digestate still contains residual protein compounds, its overall protein content is lower than that of fresh food waste due to prior degradation during the anaerobic digestion process. As a result, increasing the proportion of RD in the mixture leads to a dilution effect, where the total protein concentration in the feed decreases.

This behaviour is reflected in the mixture (MIX), where protein concentration gradually declines as the recirculation ratio increases. Unlike carbohydrates, which accumulate due to incomplete degradation, proteins are more readily broken down into amino acids and further converted into intermediate compounds such as ammonia. Consequently, less residual protein remains in the digestate to be reintroduced into the system.

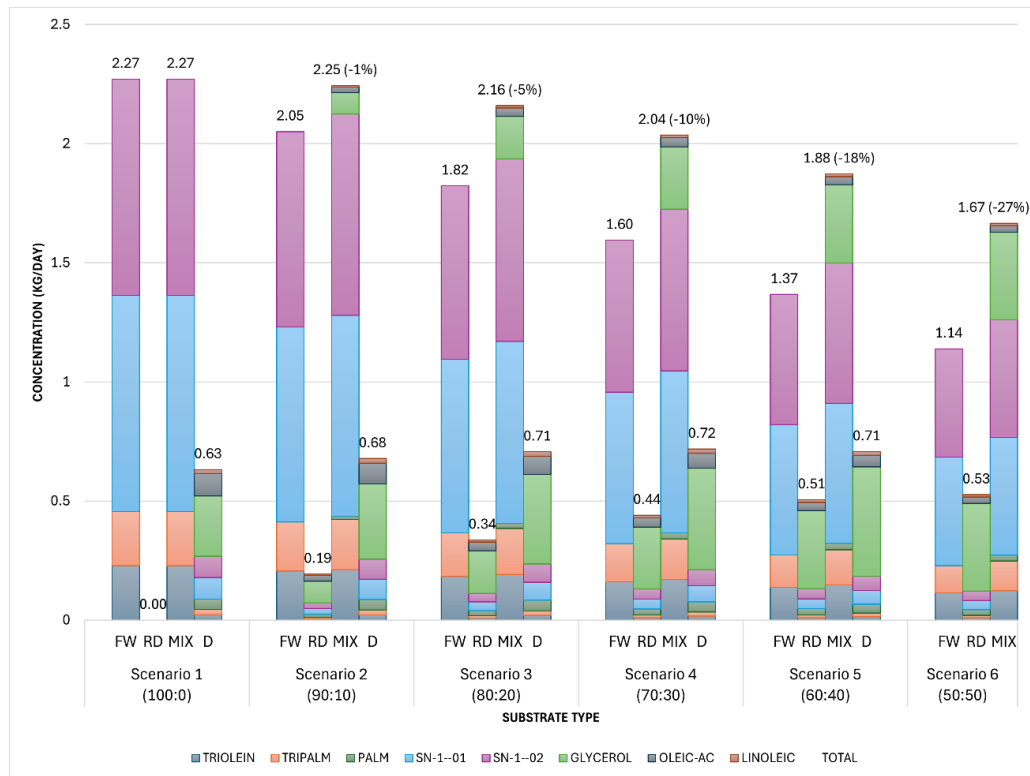


Figure 6. Effect of different recirculation ratio on lipid concentration (kg/day) in Food Waste (FW), Recirculated Digestate (RD), Mixture Substrate (MIX), and Digestate (D)
Source: Authors' simulation results (2024)

For lipids, the main constituents in the mixed substrate across all scenarios were 1-Palmitoyl-2-oleoyl-sn-glycerol (SN-1-01) and 1-O-Palmitoyl-2-O-linoleoyl-D-glycerol (SN-1-02). A similar contrasting trend is also typically observed for lipids as shown in **Figure 6**, where their concentration decreases from 1% at 10% recirculation ratio (Scenario 2) and reach the reduction of 27% at 50% recirculation ratio (Scenario 6). Although, lipid concentration is much higher than the other major nutrient. Lipids are generally more biodegradable under anaerobic conditions and are efficiently converted into long-chain fatty acids and subsequently into biogas. Therefore, the recirculated digestate contributes relatively little lipid content compared to fresh substrate, reinforcing the overall reduction in lipid concentration within the mixture.

Overall substrate characteristics

While digestate recirculation increases carbohydrate concentration due to the persistence of partially degraded compounds, it reduces protein and lipid concentrations due to their more effective degradation during the digestion process. This contrast highlights the different biodegradability and conversion pathways of major organic components in anaerobic digestion.

Effect of recirculation ratio on methane production

The practice of adding recirculated digestate at specific proportions can be applied to enhance the stability and performance of the biogas production process (Müller et al., 2017). Methane volume is a key indicator for evaluating the effectiveness of the anaerobic digestion process, as methane constitutes the primary component of biogas, which is the main product of anaerobic treatment. Methane production is quantified as the amount of methane generated

per unit mass of liquid contained in the substrate over a specified period. The simulated methane production results are presented in **Figure 7**.

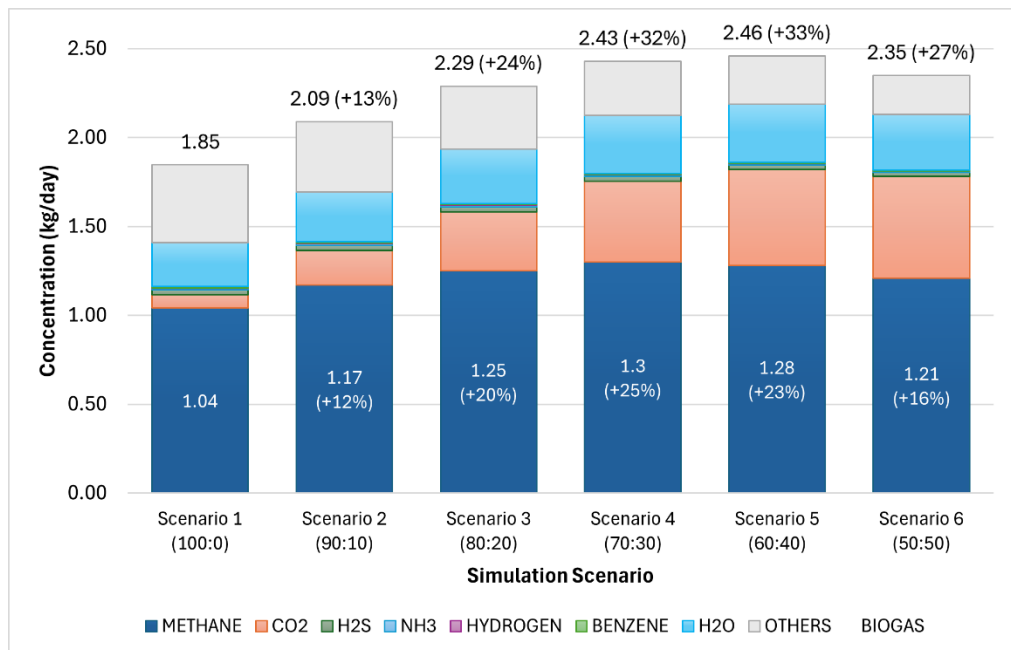


Figure 7. The effect of different recirculation ratio on biogas concentration
Source: Authors' simulation results (2024)

Recirculation ratio of 0 up to 40%: inclining concentration

The simulation results show that digestate recirculation significantly affects both biogas and methane production. Biogas and methane production exhibit a clear increasing trend as the recirculation ratio increases, although the magnitude of improvement becomes progressively less significant at higher levels. Total biogas concentration rises from 1.85 kg/day in Scenario 1 to 2.09 kg/day in Scenario 2, which is 13% higher, then continues to increase to 2.29 kg/day (+24%) in Scenario 3, and 2.43 kg/day (+32%) in Scenario 4, before reaching a peak value of 2.46 kg/day in Scenario 5 (employing a substrate composition of 60% food waste, and 40% digestate), which is equivalent to 33% higher compared to Scenario 1 without digestate addition. The results indicates that while the concentration continues to increase, the incremental gain between scenarios becomes smaller as the system approaches its optimal condition.

A similar pattern is observed for methane, although it shows a slightly different trend compared to the overall biogas concentration, as it reaches its peak earlier. Methane production increases from 1.04 kg/day in Scenario 1 to 1.17 kg/day in Scenario 2, which is equivalent to 12% higher compared to Scenario 1 without digestate addition and further reaches its maximum at 1.30 kg/day in Scenario 4, which is equivalent to approximately 25% higher compared to Scenario 1 without digestate addition. After this point, methane slightly decreases to 1.28 kg/day, or about 23% higher than Scenario 1, indicating a mild decline rather than continued growth at higher recirculation ratios. This difference in trend suggests that the increase in total biogas concentration beyond Scenario 4 is not primarily driven by methane, but rather by the continued rise of other gas components. In other words, while methane production begins to plateau.

Recirculation ratio over 40%: declining concentration

At higher recirculation ratios, both total biogas and methane begin to decline, although they remain above the baseline condition. Total biogas concentration decreases from its peak of 2.46 kg/day in Scenario 5 to 2.35 kg/day in Scenario 6, which is still 27% higher than Scenario 1. A more pronounced reduction is observed for methane, which drops from 1.3 kg/day (about 25% higher than Scenario 1) to 1.21 kg/day, which is around 16% higher than Scenario 1. This early decline in methane compared to total biogas indicates that methanogenesis is more sensitive to excessive recirculation conditions.

The same trend is also reflected in the volumetric data, where biogas production reaches its peak at 3098.32 L/day in Scenario 5 (approximately 32% higher than Scenario 1), and then decreases to 2944.27 L/day in Scenario 6. This confirms that although digestate recirculation continues to provide benefits compared to the no-recirculation condition, excessive application leads to diminishing returns.

This result suggests that the system has surpassed its optimal recirculation threshold, leading to reduced process efficiency. The continued presence of relatively high total biogas alongside a stronger decline in methane implies that non-methane gases (such as CO₂) still contribute significantly to the total gas production, while methane formation becomes increasingly limited. This may be caused by the accumulation of inhibitory compounds such as free ammonia, reduced availability of readily biodegradable substrate due to excessive recycling, or imbalances in microbial activity, particularly affecting methanogenic archaea, which are generally more sensitive to environmental changes than acidogenic bacteria.

Overall methane production performance

In summary, digestate recirculation enhances both total biogas and methane production compared to the baseline condition, but with an optimal range beyond which the benefits diminish. Total biogas concentration reaches a peak of 2.46 kg/day, which is equivalent to about 25% higher compared to Scenario 1 without digestate addition, while methane attains its maximum earlier at 1.30 kg/day, or approximately 20% higher than Scenario 1. The earlier peak observed in methane compared to total biogas indicates that further increases in biogas at higher recirculation ratios are increasingly influenced by non-methane components such as CO₂. In this study, the highest methane yield was achieved with the addition of 30% digestate. This aligns with the findings of (Müller et al., 2017), who reported that mixing substrate with 27% recirculated digestate can improve the fermentation process and significantly increase methane production.

Thus, these results suggest that digestate recirculation improves system performance through enhanced microbial activity and nutrient recycling, but only up to an optimal level. Beyond this point, the reduction in methane yield alongside the continued presence of other gases indicates a shift in process efficiency and the onset of limiting factors. Therefore, careful optimization of the recirculation ratio is necessary to maximize methane production while maintaining process stability and efficiency.

Analysis of biogas quality and composition

Although the total methane production increases with digestate recirculation, its proportion in the biogas shows a declining trend, as shown in **Figure 8**. The methane composition decreases from 56.5% in Scenario 1 to approximately 51% at the highest recirculation ratio (Scenario 6). This indicates that, despite higher overall gas production, the

relative share of methane becomes lower as more digestate is recirculated. In other words, digestate addition does not improve biogas quality in terms of methane content. This result suggests that the increase in total biogas is not primarily driven by methane formation, but rather by the growing contribution of other gas components.

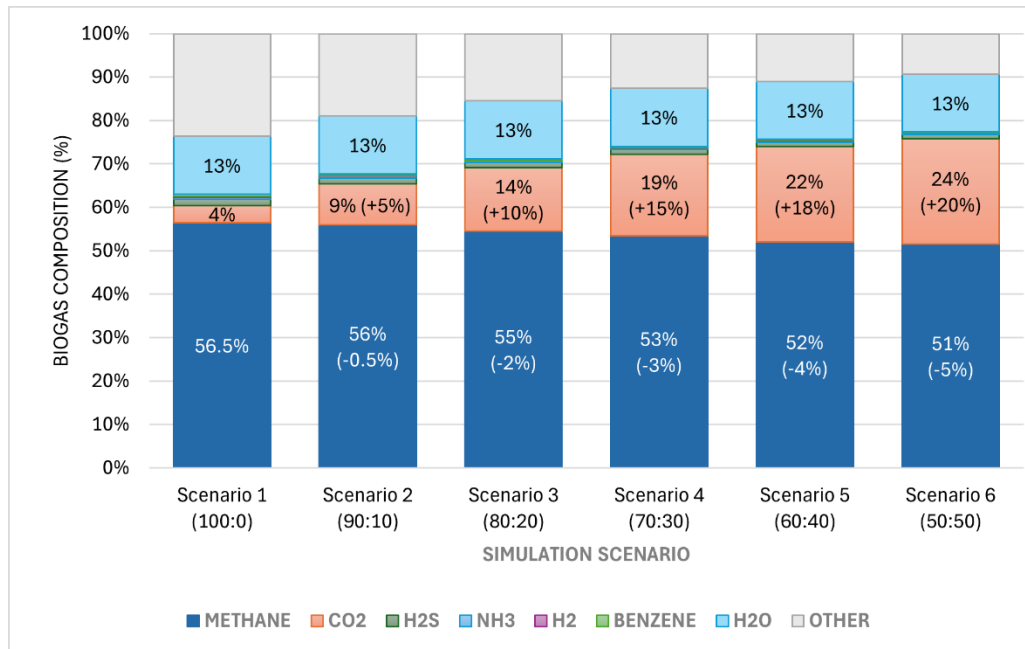


Figure 8. The effect of different recirculation ratio on biogas composition in percentage
Source: Authors' simulation results (2024)

Carbon dioxide gas content

In contrast to methane, carbon dioxide (CO₂) shows a significant and consistent increase with higher recirculation ratios. CO₂ composition rises from about 4% in Scenario 1 to approximately 24% in Scenario 6, making it the main contributor to the shift in biogas composition. This substantial increase indicates that additional digestate enhances pathways that leads to CO₂ generation. Such behaviour may be associated with intensified acidogenesis and acetogenesis, where intermediate compounds are further converted into CO₂ rather than methane. It may also reflect changes in system conditions, such as pH or ammonia levels, that slightly suppress methanogenic activity while still allowing overall gas production to continue.

Other gasses content

Other gas components show relatively minor changes compared to methane and CO₂. Hydrogen sulfide (H₂S) slightly decreases from around 1.4% to 1%. Meanwhile, components such as water vapor (H₂O), ammonia (NH₃), hydrogen (H₂), and benzene remain relatively stable across all scenarios. Water vapor maintains a consistently high proportion of around 13%, unaffected by recirculation ratio. Ammonia remains low, at approximately 0.3–0.5% (around 0.0087–0.01 kg/day), suggesting a minimal risk of ammonia inhibition on methanogenesis. Similarly, hydrogen and benzene remain at trace levels, indicating that recirculation does not significantly influence their formation.

Overall biogas quality

The application of digestate recirculation could increase total biogas production but leads to a decline in biogas quality in terms of methane content. The reduction in methane percentage, combined with a significant rise in CO₂, indicates a shift in the dominant biochemical pathways within the system. While other gas components remain relatively stable, the increasing presence of CO₂ highlights the importance of optimizing recirculation ratios to balance biogas quantity and quality, particularly when methane is the desired end product.

Based on the simulation and analysis results, the relatively low methane composition and the high CO₂ content indicate the need for further biogas upgrading into biomethane. This upgrading process is essential to effectively utilize methane as an environmentally friendly fuel, while also minimizing the risk of damage and operational failure in downstream energy conversion units.

CONCLUSION

Based on the research work done in this study, the main conclusion is there is a linear correlation observed between the addition of recirculated digestate and the increase in methane production. The results demonstrate that digestate recirculation could enhance methane production by up to 33%. The highest possible methane yield was achieved at a recirculation ratio of 30%, up to 25% higher compared to baseline scenario. However, the increase in CO₂ concentration should be considered a significant concern, as it reduces biogas quality by lowering the methane fraction and may negatively affect the performance and reliability of downstream energy conversion systems. Therefore, optimization of digestate recirculation ratios and the implementation of biogas upgrading processes are necessary to ensure efficient and sustainable biomethane utilization. This study provides valuable insights into the sustainable utilization of digestate by demonstrating its suitability as a substrate for anaerobic digestion and its potential for renewable energy recovery. By addressing key technical challenges such as dosage optimization and microbial dynamics, this study lays the foundation for improving anaerobic digestion processes and supporting environmentally friendly and resource-efficient waste management practices. Since this study employed a fixed ORL-HRT configuration to specifically assess the effects of substrate ratio under controlled and stable conditions, broader evaluations should explore future investigations of OLR and HRT to better understand the system performance under dynamic and practical operating environments.

REFERENCES

- Adesiyun, A. I., Ayeleru, O. O., Modekwe, H. U., Nyam, T. T., Ameh, V. I., & Ramatsa, I. M. (2024). Effects of process parameters on biogas production from food waste using aspen plus simulator. *Waste Management Bulletin*, 2(3), 289–295. <https://doi.org/10.1016/j.wmb.2024.08.010>
- Aguilar, M. C., Wang, Y. D., Roskilly, T., Pathare, P. B., & Lamidi, R. O. (2017). Biogas from anaerobic co-digestion of food waste and primary sludge for cogeneration of power and heat. *Energy Procedia*, 142, 70–76. <https://doi.org/10.1016/j.egypro.2017.12.012>
- Anaya Menacho, W., Mazid, A. M., & Das, N. (2022). Modelling and analysis for biogas production process simulation of food waste using Aspen Plus. *Fuel*, 309, 122058. <https://doi.org/10.1016/j.fuel.2021.122058>

- Ariunbaatar, J., Scotto Di Perta, E., Panico, A., Frunzo, L., Esposito, G., Lens, P. N. L., & Pirozzi, F. (2015). Effect of ammoniacal nitrogen on one-stage and two-stage anaerobic digestion of food waste. *Waste Management*, 38, 388–398. <https://doi.org/10.1016/j.wasman.2014.12.001>
- Beale, D. J., Karpe, A. V., McLeod, J. D., Gondalia, S. V., Muster, T. H., Othman, M. Z., Palombo, E. A., & Joshi, D. (2016). An ‘omics’ approach towards the characterisation of laboratory scale anaerobic digesters treating municipal sewage sludge. *Water Research*, 88, 346–357. <https://doi.org/10.1016/j.watres.2015.10.029>
- Bhatt, A. H., & Tao, L. (2020). Economic Perspectives of Biogas Production via Anaerobic Digestion. *Bioengineering*, 7(3), 74. <https://doi.org/10.3390/bioengineering7030074>
- Bonk, F., Popp, D., Weinrich, S., Sträuber, H., Kleinsteuber, S., Harms, H., & Centler, F. (2018). Ammonia Inhibition of Anaerobic Volatile Fatty Acid Degrading Microbial Communities. *Frontiers in Microbiology*, 9. <https://doi.org/10.3389/fmicb.2018.02921>
- Browne, J. D., & Murphy, J. D. (2013). Assessment of the resource associated with biomethane from food waste. *Applied Energy*, 104, 170–177. <https://doi.org/10.1016/j.apenergy.2012.11.017>
- Budhraj, N. (2024). Simulation and optimization for biohydrogen production potential of various organic waste via anaerobic digestion. *Fuel*, 360, 130563. <https://doi.org/10.1016/j.fuel.2023.130563>
- Ekstrand, E.-M., Björn, A., Karlsson, A., Schnürer, A., Kandars, L., Yekta, S. S., Karlsson, M., & Moestedt, J. (2022). Identifying targets for increased biogas production through chemical and organic matter characterization of digestate from full-scale biogas plants: what remains and why? *Biotechnology for Biofuels and Bioproducts*, 15(1), 16. <https://doi.org/10.1186/s13068-022-02103-3>
- Fisgativa, H., Tremier, A., & Dabert, P. (2016). Characterizing the variability of food waste quality: A need for efficient valorisation through anaerobic digestion. *Waste Management*, 50, 264–274. <https://doi.org/10.1016/j.wasman.2016.01.041>
- García-Diéguez, C., Bernard, O., & Roca, E. (2013). Reducing the Anaerobic Digestion Model No. 1 for its application to an industrial wastewater treatment plant treating winery effluent wastewater. *Bioresource Technology*, 132, 244–253. <https://doi.org/10.1016/j.biortech.2012.12.166>
- Han, W., Liu, D. N., Shi, Y. W., Tang, J. H., Li, Y. F., & Ren, N. Q. (2015). Biohydrogen production from food waste hydrolysate using continuous mixed immobilized sludge reactors. *Bioresource Technology*, 180, 54–58. <https://doi.org/10.1016/j.biortech.2014.12.067>
- Jankauskienė, J., Laužikė, K., & Kaupaitė, S. (2024). The Use of Anaerobic Digestate for Greenhouse Horticulture. *Agronomy*, 14(10), 2437. <https://doi.org/10.3390/agronomy14102437>
- Kiran, E. U., & Trzcinski, A. P. (2017). Optimizing the Conversion of Food Waste to Sugars using Fungal Enzymes Cronicon EC MICROBIOLOGY Optimizing the Conversion of Food Waste to Sugars using Fungal Enzymes. <https://www.researchgate.net/publication/320215895>
- Liu, C., Li, H., Zhang, Y., & Liu, C. (2016). Improve biogas production from low-organic-content sludge through high-solids anaerobic co-digestion with food waste. *Bioresource Technology*, 219, 252–260. <https://doi.org/10.1016/j.biortech.2016.07.130>
- Lopez, V. M., De la Cruz, F. B., & Barlaz, M. A. (2016). Chemical composition and methane potential of commercial food wastes. *Waste Management*, 56, 477–490. <https://doi.org/10.1016/j.wasman.2016.07.024>
- Mihi, M., Ouhammou, B., Aggour, M., Daouchi, B., Naaim, S., El Mers, E. M., & Kousksou, T. (2024). Modeling and forecasting biogas production from anaerobic digestion process

- for sustainable resource energy recovery. *Heliyon*, 10(19), e38472. <https://doi.org/10.1016/j.heliyon.2024.e38472>
- Mohammadianroshanfekr, M., Pazoki, M., Pejman, M. B., Ghasemzadeh, R., & Pazoki, A. (2024). Kinetic modeling and optimization of biogas production from food waste and cow manure co-digestion. *Results in Engineering*, 24, 103477. <https://doi.org/10.1016/j.rineng.2024.103477>
- Möller, K. (2015). Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development*, 35(3), 1021–1041. <https://doi.org/10.1007/s13593-015-0284-3>
- Moonsamy, T. A., Rajauria, G., Priyadarshini, A., & Jansen, M. A. K. (2024). Food waste: analysis of the complex and variable composition of a promising feedstock for valorisation. *Food and Bioproducts Processing*, 148, 31–42. <https://doi.org/10.1016/j.fbp.2024.08.012>
- Müller, F., Maack, G.-C., & Buescher, W. (2017). Effects of Biogas Substrate Recirculation on Methane Yield and Efficiency of a Liquid-Manure-Based Biogas Plant. *Energies*, 10(3), 325. <https://doi.org/10.3390/en10030325>
- Pagliaccia, P., Gallipoli, A., Gianico, A., Gironi, F., Montecchio, D., Pastore, C., di Bitonto, L., & Braguglia, C. M. (2019). Variability of food waste chemical composition: Impact of thermal pre-treatment on lignocellulosic matrix and anaerobic biodegradability. *Journal of Environmental Management*, 236, 100–107. <https://doi.org/10.1016/j.jenvman.2019.01.084>
- Poe, N. E., Yu, D., Jin, Q., Ponder, M. A., Stewart, A. C., Ogejo, J. A., Wang, H., & Huang, H. (2020). Compositional variability of food wastes and its effects on acetone-butanol-ethanol fermentation. *Waste Management*, 107, 150–158. <https://doi.org/10.1016/j.wasman.2020.03.035>
- Qian, S., Chen, L., Xu, S., Zeng, C., Lian, X., Xia, Z., & Zou, J. (2025). Research on Methane-Rich Biogas Production Technology by Anaerobic Digestion Under Carbon Neutrality: A Review. *Sustainability*, 17(4), 1425. <https://doi.org/10.3390/su17041425>
- Rajendran, K., Kankanala, H. R., Lundin, M., & Taherzadeh, M. J. (2014). A novel process simulation model (PSM) for anaerobic digestion using Aspen Plus. *Bioresource Technology*, 168, 7–13. <https://doi.org/10.1016/j.biortech.2014.01.051>
- Salama, E.-S., Saha, S., Kurade, M. B., Dev, S., Chang, S. W., & Jeon, B.-H. (2019). Recent trends in anaerobic co-digestion: Fat, oil, and grease (FOG) for enhanced biomethanation. *Progress in Energy and Combustion Science*, 70, 22–42. <https://doi.org/10.1016/j.pecs.2018.08.002>
- Selvam, A., Ilamathi, P. M. K., Udayakumar, M., Murugesan, K., Banu, J. R., Khanna, Y., & Wong, J. (2021). Food Waste Properties. In *Current Developments in Biotechnology and Bioengineering* (pp. 11–41). Elsevier. <https://doi.org/10.1016/B978-0-12-819148-4.00002-6>
- Shen, F., Yuan, H., Pang, Y., Chen, S., Zhu, B., Zou, D., Liu, Y., Ma, J., Yu, L., & Li, X. (2013). Performances of anaerobic co-digestion of fruit & vegetable waste (FVW) and food waste (FW): Single-phase vs. two-phase. *Bioresource Technology*, 144, 80–85. <https://doi.org/10.1016/j.biortech.2013.06.099>
- Slopiecka, K., Liberti, F., Massoli, S., Bartocci, P., & Fantozzi, F. (2022). Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants. *Energy Nexus*, 5, 100049. <https://doi.org/10.1016/j.nexus.2022.100049>
- Song, L., Yang, D., Liu, R., Liu, S., & Dai, X. (2023). The dissolution of polysaccharides and amino acids enhanced lactic acid production from household food waste during pretreatment process. *Science of The Total Environment*, 864, 161068. <https://doi.org/10.1016/j.scitotenv.2022.161068>

- Vaneekhaute, C., Claeys, F. H. A., Tack, F. M. G., Meers, E., Belia, E., & Vanrolleghem, P. A. (2018). Development, implementation, and validation of a generic nutrient recovery model (NRM) library. *Environmental Modelling & Software*, 99, 170–209. <https://doi.org/10.1016/j.envsoft.2017.09.002>
- Wang, L., Aziz, T. N., & de los Reyes, F. L. (2013). Determining the limits of anaerobic co-digestion of thickened waste activated sludge with grease interceptor waste. *Water Research*, 47(11), 3835–3844. <https://doi.org/10.1016/j.watres.2013.04.003>
- Weiland, P. (2010). Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology*, 85(4), 849–860. <https://doi.org/10.1007/s00253-009-2246-7>
- Xue, S., Wang, Y., Lyu, X., Zhao, N., Song, J., Wang, X., & Yang, G. (2020). Interactive effects of carbohydrate, lipid, protein composition and carbon/nitrogen ratio on biogas production of different food wastes. *Bioresource Technology*, 312, 123566. <https://doi.org/10.1016/j.biortech.2020.123566>
- Yan, B. H., Selvam, A., & Wong, J. W. C. (2016). Innovative method for increased methane recovery from two-phase anaerobic digestion of food waste through reutilization of acidogenic off-gas in methanogenic reactor. *Bioresource Technology*, 217, 3–9. <https://doi.org/10.1016/j.biortech.2016.03.116>
- Yang, Z., Yang, D., Hua, Y., Chen, X., Wang, X., Gong, H., Dong, B., Li, X., & Dai, X. (2024). Dual optimization in anaerobic digestion of rice straw: Effects HRT and OLR coupling on methane production in one-stage and two-stage systems. *Journal of Environmental Management*, 370, 123041. <https://doi.org/10.1016/j.jenvman.2024.123041>
- Zhang, W., Xing, W., & Li, R. (2018). Real-time recovery strategies for volatile fatty acid-inhibited anaerobic digestion of food waste for methane production. *Bioresource Technology*, 265, 82–92. <https://doi.org/10.1016/j.biortech.2018.05.098>