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Application of a Full-Scale Horizontal Anaerobic Digester for the Co-Digestion of Pig Manure, Food Waste, Excretion, and Thickened Sewage Sludge

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Abstract: Many laboratory- and pilot-scale studies on anaerobic co-digestion have been conducted in Republic of Korea; however, studies on full-scale demonstration facilities are lacking. This study aimed to present a successful case of a large-scale anaerobic co-digestion facility in Republic of Korea for biogas generation from four organic wastes (pig manure, food waste, excretion, and thickened sewage sludge) using a horizontal anaerobic digester. A preliminary biochemical methane potential test was performed for the individual and mixed organic waste to design a treatment facility for 320 m^3/day of organic waste generated in Seosan City. Subsequently, a horizontal anaerobic digester with a 35 day-retention time (based on 320 m^3/day input) was constructed. Each organic waste was placed in an anaerobic reactor after pretreatment. The input was gradually increased after the first seeding, and the operation continued for 158 days. Total and volatile solids made up 4.1% and 3.3%, respectively. Throughout the operating period, the digester temperature was maintained at 35–40 °C for mesophilic digestion, and the pH was maintained at 7–8. The average organic matter removal efficiency (volatile solids basis) was 64% and the methane gas production rates were 0.35, 0.6, 0.26, 0.28, and 0.39 Nm^3CH_4/kg vs. for pig manure, food waste, excretion, thickened sewage sludge, and mixed waste, respectively, resulting in an average methane content of the biogas 68.8%.

Keywords: organic waste; anaerobic co-digestion; bio-gasification; horizontal mixing; mixed substrates; methane gas production rate

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1. Introduction

1.1. Current Status of Bio-Gasification in Republic of Korea

In 2008, the Korean Ministry of Environment established the "Comprehensive policy of waste resource and biomass" (2008, Ministry of Environment) [1] to continuously expand bio-gasification facilities rather than disposing of organic waste resources. The proportions of the main organic waste resources generated and treated in 2019 were 55.93 million tons/day (86%) of livestock manure, 5.22 million tons/day (8%) of food waste, and 4.22 million tons/day (6%) of sewage sludge. Compositing/liquid fertilization accounted for 76.7% of treatments, purification treatment for 10.4%, bio-gasification for 5.7%, feed conversion for 2.9%, and others for 4.3% [2], highlighting that the bio-gasification proportion is low.

The Korean government has been continuously expanding bio-gasification facilities to achieve this, and 110 bio-gasification facilities are in operation as of 2021 [3]. Currently, most are anaerobic mono-digestion facilities, and efforts are continuously being made to secure anaerobic co-digestion facilities that treat food waste, excretion, livestock manure, and sewage sludge.

1.2. Anaerobic Co-Digestion

Anaerobic co-digestion has been shown to improve the efficiency of organic waste treatments with different properties and complementary characteristics and offers significant economic advantages. The anaerobic mono-digestion treatment of organic waste can be challenging due to nutrient imbalances and a lack of microbial diversity. However, anaerobic co-digestion has been shown to effectively address both challenges without the need for additives [4–7]. Anaerobic co-digestion has many essential factors, the most important of which are described below.

Substrate is a crucial factor for anaerobic digestion efficiency. It is converted into biogas through biochemical processes, such as hydrolysis, acidogenic fermentation, acetogenesis, and methanogenesis, that accompany anaerobic digestion [8]. The velocity and rate of conversion into methane gas vary with the substrate's chemical composition. The substrate, largely composed of carbohydrates, proteins, and fats, is converted into simpler molecules through a biochemical process and finally into methane and other substances [9,10]. Protein-rich organic substrates, such as livestock manure, have a high energy content and produce relatively high volumes of methane. A high concentration of ammonia interferes with microorganism activity and increases the instability of anaerobic digestion, causing system failure. However, suitable co-substrate-like food waste can adjust the C/N ratio to its optimum value. Carbohydrate-rich organic substrates, such as food waste, contain considerable amounts of simple sugars and disaccharides that are easily decomposed by methanogenic microorganisms and can easily produce volatile fatty acids (VFAs). However, a decrease in pH because of VFA accumulation, a high carbon-to-nitrogen (C/N) ratio, and concentration of heavy metals and toxic substances can cause challenges in anaerobic digestion. Suitable co-substrate-like animal manure can adjust the VFA concentration. Additionally, fat-rich organic substrates can be easily decomposed and produce large volumes of biogas. However, challenges such as blocking, adsorption to biomass, and foaming may occur, where carbohydrate-rich co-substrate can be used to adjust the nutritional balance [11–13].

The optimal pH range for biogas production in an anaerobic digester is 6.8–7.2. Acidogenic microorganisms are less sensitive to pH and can tolerate a pH range of 4.0–8.5; the optimal pH for hydrolysis and acidogenesis is 5.5–6.5 [14,15]. In contrast, methanogenic microorganisms are highly sensitive to pH, and the appropriate pH is approximately 7. Therefore, a two-stage digester is sometimes used to divide the anaerobic digester into two parts with different pH ranges to maximize the efficiency of anaerobic digestion. Therefore, pH is an important factor in determining the health of anaerobic digesters. Methane production may not be successful if the pH is not maintained within the optimal range, such as when the pH drops as a result of excessive VFA during the anaerobic digestion of a single substrate, including high-concentration food waste [12,16]. Anaerobic co-digestion of food waste with a pH of <4 and livestock manure with a pH of >8 can lead to increased gas production compared to separate digestion provided that the feedstock mixture is adjusted to maintain an optimal pH of 6.5–7.5 throughout the process [2].

According to previous studies on biogas production through anaerobic digestion, the typical C/N ratio is 20–30 [14,17–19]. However, determining the optimal C/N ratio is challenging because it depends on the chemical composition and biodegradability of the substrate [20]. However, system instability can be reduced if the C/N ratio is maintained within the normal range [12]. The challenges that can occur when an appropriate C/N ratio is not maintained are as follows: a high C/N ratio may cause excessive VFA generation, and a low C/N ratio may lead to excessive generation of total ammonia nitrogen. These are intermediate products of the metabolic process that interfere with the production of methane [21]. Methane production can be increased by maintaining an appropriate C/N ratio in anaerobic co-digestion, such as swine manure, rice straw mix [21], cow manure, and energy crop mix [22].

1.3. Design of a Full Scale Anaerobic Co-Digester

Anaerobic digestion (AD) generally works well on a laboratory or intermediate scale, but problems may arise when scaling up to larger reactors [9]. Potential issues include unpredictable substance behavior in the mixture, leading to problems such as odor, fermentation cessation, or slowed fermentation rates; difficulty with solid waste processing, which can accumulate within the reactor and hinder the fermentation process; difficulties maintaining proper temperature control, which can lead to overheating in some areas and slow fermentation rates in others; and difficulty maintaining consistent flow rates, which can affect both the speed and stability of the fermentation process. To address these challenges, effective flow control and characterization of mixture properties are required in large-scale AD reactors. Additionally, appropriate technology and operational strategies must be adopted to ensure the stability and efficiency of large-scale anaerobic digestion.

In order to ensure the stable operation of large-scale anaerobic digesters, mixing is a crucial factor. Many mixing devices have been applied to anaerobic digestion; they can be classified largely as mechanical, hydraulic, and pneumatic mixing devices [23]. Most anaerobic digesters used in Korea are vertical-flow cylindrical digesters that use mechanical mixing. If not mixed properly, stratification occurs in the anaerobic digester, causing light materials to accumulate in the upper layer and heavy particles to sink to the lower layer. Subsequently, anaerobic digestion occurs only in the middle layer, resulting in a shorter retention time [24,25]. This phenomenon frequently occurs in anaerobic digesters installed in Korea, as reported in a Dongdaemun Environmental Resources Center case study, a food waste treatment facility in Seoul fitted with a dry anaerobic digestion system [26]. Mixing is crucial when treating food waste with high total solids (TS) rather than low TS [25]. Therefore, the shape of the anaerobic digester and the mixing of waste are important factors. A report has described the stable treatment of high-concentration food waste at 15 m^3/day using effective mixing with a horizontal anaerobic digester [27]. Thus, a horizontal anaerobic digester equipped with large impellers can be a viable alternative to solve the existing mixing problems.

With the recent development of computer models and the complexity of mathematical expressions for the anaerobic digestion process, full-scale performance can be predicted to a relatively meaningful degree through batch experiments and kinetic models [28,29]. In Korea, the size design and methane production rate of anaerobic digesters for various substrates are predicted using biochemical methane potentials (BMPs), specific organic loading, and kinetic models.

This study primarily aimed to provide information (design and operation data) on Republic of Korea's first large-scale anaerobic co-digestion facility, which processes 320 m^3/day of four types of organic waste (food waste, pig manure, excretion, and thickened sewage sludge) generated in Seosan City using a horizontal anaerobic digester.

2. Materials and Methods

Substrate characteristics were investigated, and the methane production rates were estimated using a BMP test to design, construct, and operate an anaerobic digestion tank equipped with a vertical agitator at 320 m^3/day using large-scale horizontal axis rotation to treat organic waste generated in Seosan City. After installing a full-scale anaerobic co-digestion plant at the Seosan City sewage treatment plant, inoculation, and operation were performed.

2.1. Substrate Characteristics

Seosan City is located in Chuncheongnam-do, Republic of Korea. In 2016, it had 174,762 habitants. The organic waste treated through anaerobic co-digestion in Seosan City is presented in Table 1. Pig manure was collected from four Seosan City livestock farms, food waste from the local food waste treatment facility, excretion from individual wastewater treatment facilities (including septic tanks) in Seosan City, and thickened sewage sludge from the thickened sewage sludge transfer pipe in the Seosan City sewage treatment plant.

The total amount was the maximum predicted amount of daily occurrence of food waste, pig manure, excretion, and thickened sewage sludge in Seosan City. Thickened sewage sludge was the sludge collected from the secondary setting tank of the Seosan Public Sewage Treatment Plant, which has a daily processing capacity of 40,000 m^3/day.

Table 1. Organic waste to be treated.

Total (m^3/d)	Food Waste (m^3/d)	Pig Manure (m^3/d)	Excretion (m^3/d)	Thickened Sewage Sludge (m^3/d)
320	50	100	70	100

The property investigation was performed by selecting sample investigation items to understand the characteristics of the food waste, pig manure, excretion, and thickened sewage sludge to be treated, as presented in Table 2.

Table 2. Organic waste sample investigation items.

Organic Waste	Number of Samples	Sampling Point	Analysis Items
Pig manure	4	Seosan City livestock farms	1. Apparent density 2. Three components method of waste (moisture, ash, combustible matter) 3. Chemical composition (C, H, O, N, S, Cl) 4. Calorific value 5. Heavy metal (As, Cd, Cr, Cu, Pb, Ni, Zn, Hg) 6. Water quality analysis (pH, biological oxygen demand [BOD]), chemical oxygen demand (COD_{Mn}), TS, VS, SS, T-N, NH_3-N, NO_2-N, T-P, PO_4-P, alkalinity, *E. coli*, normal hexane level
Food waste	2	Food waste treatment facility in Seosan STP	
Excretion	1	Excreta treatment facility in Seosan STP	
Thickened sewage sludge	1	Thickened sewage sludge transfer pipe in Seosan STP	

2.2. BMP Test

A BMP test was performed on each substrate, including food waste, pig manure, excretion, thickened sewage sludge, and mixed waste, to design a full-scale anaerobic digester that targets the methane production rates listed in Table 3.

Table 3. Target methane production rates (Nm^3CH_4/kg VS).

Pig Manure	Food Waste	Excretion	Thickened Sewage Sludge
0.27	0.47	0.20	0.22

The sludge used for inoculation in the BMP test originated from the Paju City anaerobic co-digestion plant that co-digests food waste and pig manure because there is no anaerobic digestion plant in Seosan City. The revised anaerobic mineral medium was prepared for the broth according to Shelton and Tiedje (1984). Subsequently, the liquid medium was heated to 300 °C for 10 min to remove dissolved oxygen, and N_2 gas was injected into the headspace of the liquid medium bottle. Subsequently, it was kept in a 35 °C incubator for the experiment. For sample analysis, the gas generated was measured daily using a 10–100 mL syringe according to the gas volume generated when the external temperature was maintained at 20 °C. Gas CH_4 and CO_2 concentrations were analyzed using a gas chromatograph (thermal conductivity detector) equipped with a Porapak Q column. For VFAs analyses, the reaction solution was analyzed using a gas chromatograph (flame ionization detector) equipped with a capillary column and autosampler.

The BMP test results are illustrated in Figures 1 and 2. The target methane production rates were reached after 26 days, and the maximum methane concentration (mixed 54.3%) was recorded on the 20th day. In addition, as the quantity of organic matter in the liquid medium bottle decreased, the methane concentration decreased.

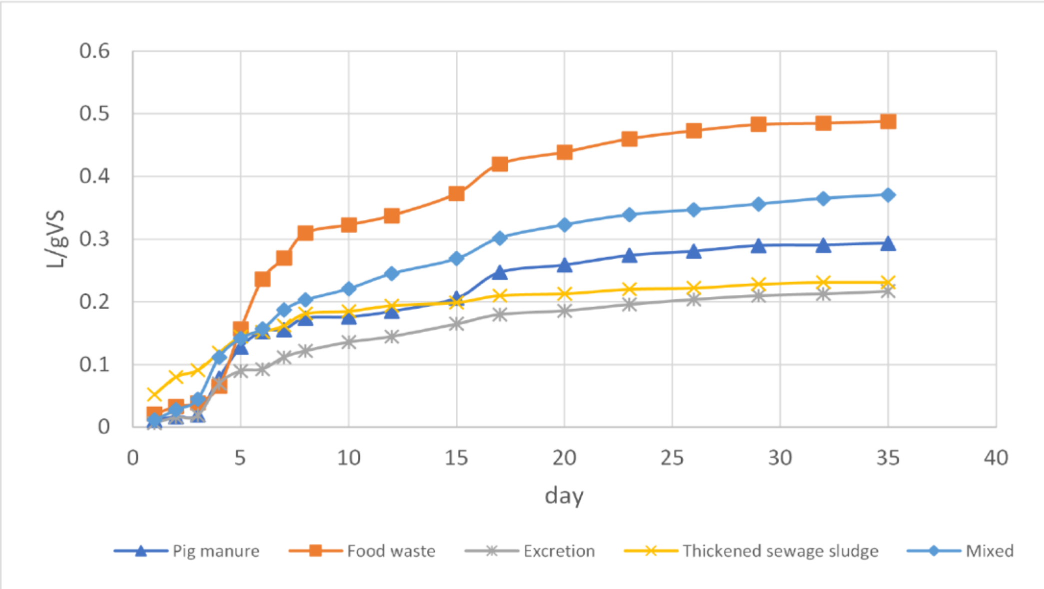


Figure 1. Cumulative biogas production (BMP test).

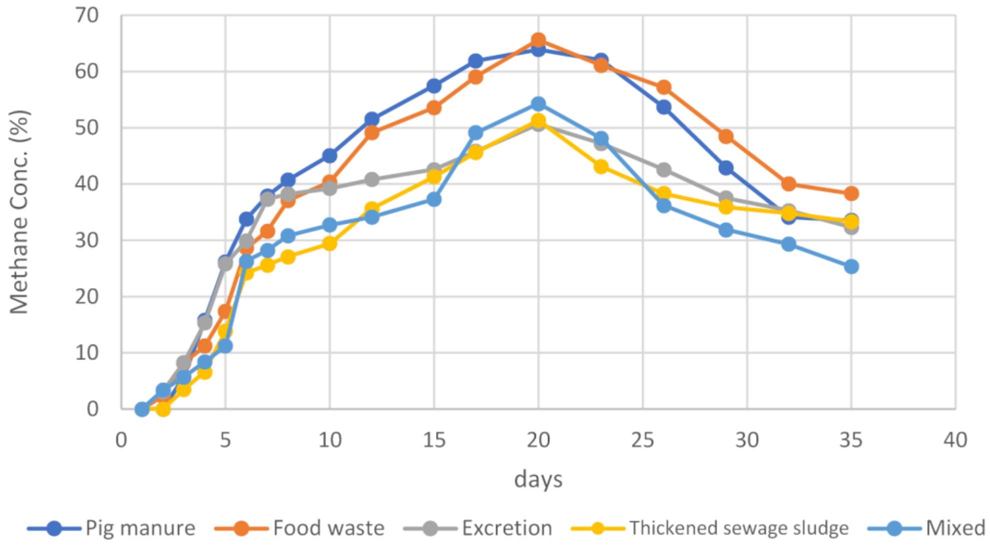


Figure 2. Biogas methane concentration (BMP test).

2.3. Full-Scale Anaerobic Co-Digestion Plant Design

Table 4 presents the characteristics of the organic wastes, which were planned through an investigation of the organic waste property to design a full-scale anaerobic co-digestion plant, which was installed in a sewage treatment plant in Seosan.

Table 4. Characteristics of organic wastes.

Contents	Pig Manure	Food Waste	Excretion	Thickened Sewage Sludge	Mixed
TS (%)	4.5	21	3.2	3.7	6.5
VS (%)	3.0	17.8	2.3	2.8	5.1
FS (%)	4.5	3.2	0.8	0.9	1.4
Moisture Content (%)	95.5	79.0	96.8	96.3	93.5

2.3.1. Design of the Pretreatment Facility

Carry-in and pretreatment facilities were installed so that the organic waste generated in Seosan City could be treated stably for 365 days (Figure 3).

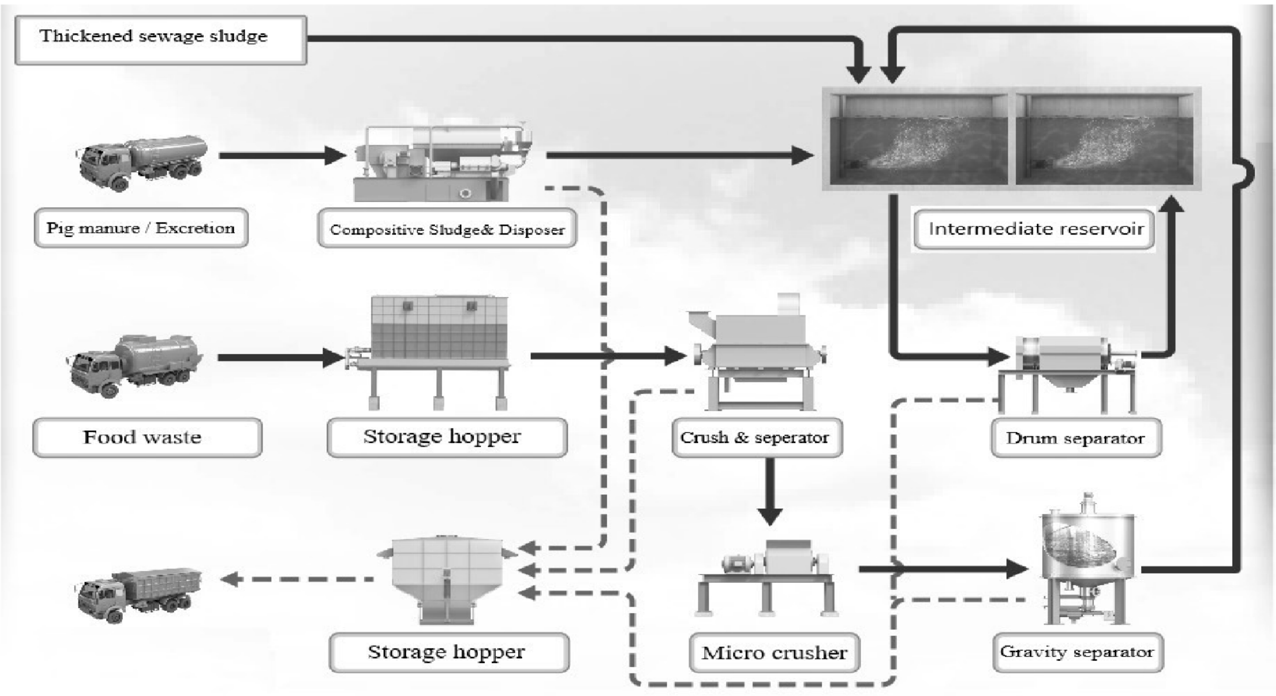


Figure 3. Carry-in and pretreatment facilities. From reference [30].

A composite sludge and disposer, a proven, reliable, and normally operating pretreatment facility installed in most livestock manure treatment facilities in Republic of Korea, was installed as a pretreatment facility for pig manure to remove coarse impurities. The food waste was stored in a storage hopper that could store food waste for three days before pretreatment using a crush and separator, a micro crusher, and a gravity separator to remove foreign matter and crush the food waste into small pieces. The thickened sewage sludge was placed in an intermediate reservoir without pretreatment. As most of the sludge was biomass, it could be directly introduced into the anaerobic digester without pretreatment. Organic wastes placed in the intermediate reservoir can be treated once more with a drum separator (5 mm perforated gap net installed) to remove coarse impurities.

2.3.2. Design of the Anaerobic Digester

The full-scale anaerobic digester comprised four systems to enable stable treatment based on the large inflow of organic waste change. The main issue many existing anaerobic digestion facilities in Republic of Korea face is inadequate mixing within the digester due to the installation of poorly performing vertical mixing system. To overcome this problem, large vertical impellers within a horizontal digester were installed to improve mixing efficiency and enable successful operation of the anaerobic co-digestion system. A horizontal anaerobic digester equipped with a horizontal agitator mixer has excellent mass transfer and mixing efficiency. As a result, the dead space within the digester can be reduced [26,31,32].

The client of this project, Seosan City, wanted to operate the anaerobic digestion facility stably. Therefore, they requested an HRT of more than 35 days, which is longer than the HRT of existing facilities in Republic of Korea, namely 20–30 days. They also wanted the anaerobic digestion tank to be designed with excellent durability. The design of this project reflects these requirements. The anaerobic digester was rectangular, installed with vertical impellers on the horizontal axis, and its HRT was over 35 days. It was a plug flow type with vertical agitation through a horizontal axis rotation (Figures 4 and 5). Impellers were exposed to the surface to prevent scum and oil layer formation, and the agitation efficiency was high, making it suitable for high-concentration organic waste treatment. An all-in-one bio-desulfurizer was installed in the upper part of the anaerobic digester to reduce the capacity of the biogas use system at the rear.

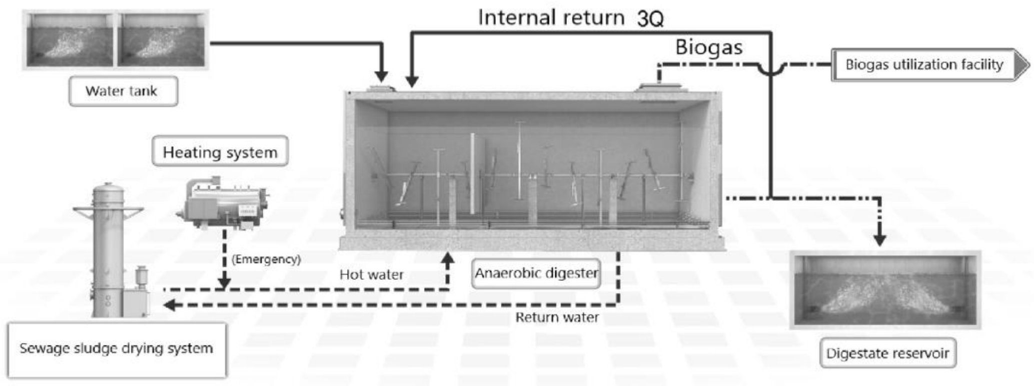


Figure 4. Anaerobic digestion system. From reference [30].

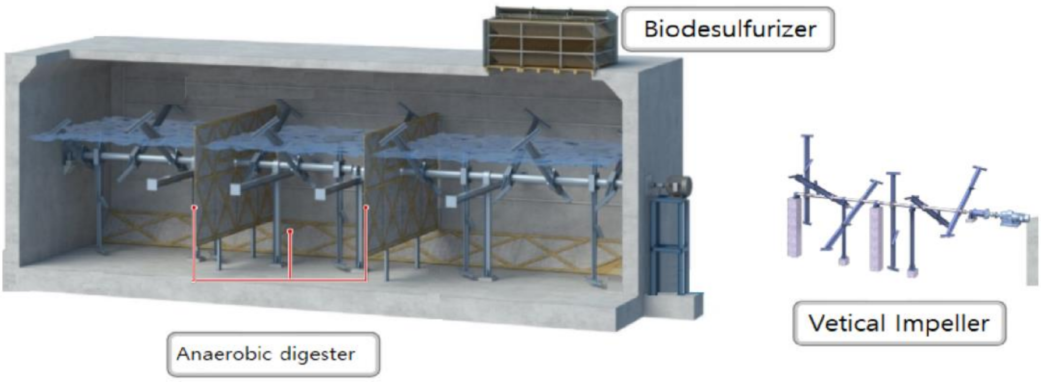


Figure 5. Anaerobic digester. From reference [30].

Furthermore, the digester size was 10.7 mW $\times$ 27.3 mL $\times$ 11.9 mH (9.5 mHe), the effective volume was 2775 m^3 $\times$ 4 reactors, and durability and structural stability were secured by applying a rectangular, reinforced concrete structure. Before installation in the plant, a simulation was run through computational fluid dynamics to predict the agitation state in the digester using Fluent v6.3.26. A detailed description of the computational fluid dynamics is provided in the appendix (the modeling purpose is shown in Appendix A, the boundary conditions are shown in Appendix B and Table A1, the analysis of results is shown in Appendices C and D, and the flow velocity and concentration distributions are shown in Figures A1 and A2).

2.3.3. Design of the Biogas Treatment Facility

The biogas produced by the anaerobic digester was utilized in downstream biogas use facilities, such as ones for gas power generation, among others. A biogas refinery facility was installed to create a suitable condition (Figure 6). The gas holder had a capacity sufficient for 3 h of biogas production. Furthermore, a dry desulfurizer was installed using $Fe(OH)_2$, a dehumidifier, and a demister. In addition, a flow meter and gas analyzer were installed to measure the biogas volume generated.

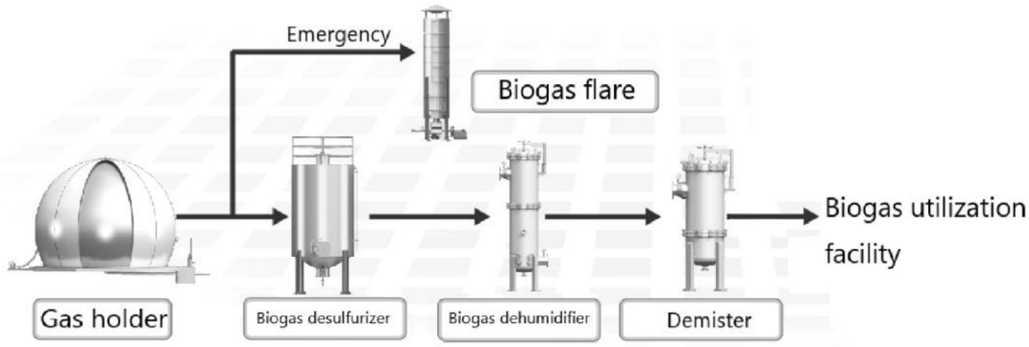


Figure 6. Biogas refinery system. From reference [30].

2.4. Anaerobic Digester Inoculation, Operating Conditions, and Introduction of Organic Waste

Inoculation is crucial in the operation of a full-scale plant, which aims to secure microorganisms in good condition. Biogas production is minimal when the inoculation sludge is in poor condition. Therefore, the sludge from the facility with the target of best properties was the inoculation among five nearby anaerobic digestion facilities (Chungju City, Cheongju City, Nonsan City, Namwon City, and Junju City). The selection was made by measuring the TS, volatile solids (VS), gas production rate, methane content, VFA, alkalinity, and pH of the digested sludge. Unlike aerobic microorganisms, anaerobic microorganisms have a slow growth rate. Therefore, the organic loading rate must gradually increase by maintaining anaerobic conditions and an optimal temperature. Organic waste was not added during the early inoculation period. Instead, starting 12 days after the start of inoculation, it was added stepwise from the log phase (proliferation stage) to the microorganism lag phase (acclimation stage). After the VFAs, alkalinity, and pH of the digestate were measured, the input was increased. The total seeding capacity was 4622 m^3, and normal operations were performed after 40 days of seeding.

The operating conditions were an organic loading rate under 1.0 kg VS/m^3/day (the anaerobic digester was designed to handle high organic loads of 3–4 kg VS/m^3/day) and maintenance of the HRT for over 35 days; the temperature of the anaerobic digester was maintained at 35–38 °C and the pH at 7–8, without separate chemical adjustment. The efficiency of the anaerobic digester was examined through daily (temperature, pH, TS, VS, and CODcr), weekly (BOD, COD_{Mn}, SS, T-N, T-P, NH_4-N, and alkalinity), and monthly (TKN, PO_4-P, and VFA) analyses.

It was planned to introduce 320 m^3/day of organic waste into the facility as a mixture of four substrates (pig manure, food waste, excretion, and thickened sewage sludge). However, for various reasons (Seosan City faced delays in securing organic waste transport vehicles, especially for food waste, because the contract with the existing waste disposal companies had not yet expired), <70% of the planned volume as obtained during the first three months. Later, over 90% of the planned volume was transferred to the facility. The removal of organic waste over 158 days is presented in Table 5.

Table 5. Monthly discharge of organic wastes.

Content		Pig Manure (m^3/day)	Food Waste (m^3/day)	Excretion (m^3/day)	Thickened Sewage Sludge (m^3/day)	Mixed (m^3/day)
Design		100	70	50	100	320
Inflow	2020.02	16	1	0	37	54
	2020.03	55	12	26	78	170
	2020.04	46	16	61	104	227
	2020.05	59	29	58	77	224
	2020.06	96	38	61	100	295
	2020.07	101	34	53	110	299
	Average	70	25	50	92	237

2.5. Statistical Analysis

Data were analyzed using the SPSS (Statistical Package for Social Science) 26.0 statistical package program after data coding and cleaning. Pearson's correlation analyses between parameters and biogas production were performed to identify the key parameters. Multiple regression analyses were performed to examine the effect of the parameters on biogas production and methane content.

3. Results and Discussion

3.1. Organic Waste Analysis Result

The organic waste analysis results are presented in Tables 6 and 7. Table 6 shows that the pH values of pig manure, food waste, excretion, and thickened sewage sludge were 8.1–8.9, 4.1–4.3, 7.3, and 6.6, respectively. Food waste had a low pH because of organic acid production, and the low pH of food waste and the high pH of pig manure complemented each other. During the operating period, the pH of the digester remained in the range of 7.1–7.9. Further, the low VS of pig manure and thickened sewage sludge was complemented by the high VS of food waste.

The sample analysis (water quality analysis) presented in Table 7 indicates that the average C/N ratio (BOD/T-N ratio) of pig manure, food waste, excretion, and thickened sewage was 6.6, 25.2, 7.1, and 7.1, respectively. The C/N ratio was maintained at an average of 7.1 during the operation period owing to the mutual complementation of organic wastes.

Table 6. Organic waste (pig manure, food waste, excretion, and thickened sewage sludge) sample analysis data.

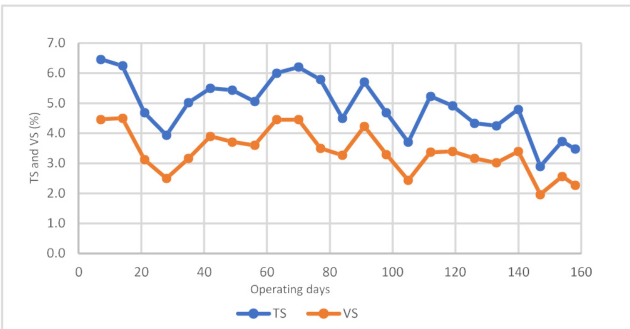
Items		Units	Farm 1	Farm 2	Farm 3	Farm 4	Food Waste 1	Food Waste 2	Excretion	Thickened Sewage Sludge	
Apparent density		kg/m^3	0.98	1.02	1.02	1.02	1.06	1.08	0.96	1	
pH			8.3	8.1	8.9	8.4	4.3	4.1	7.3	6.6	
Three components	Moisture	%	96.9		96.8	97.2	96.8	80	79.2	96.9	96.4
	Ash		0.8		0.9	0.7	1	2.2	2.7	0.7	1.2
	Combustible		2.3		2.3	2.1	2.2	17.8	18.1	2.5	2.5
	Total		100		100	100	100	100	100	100	100
TS		%	3.1		3.2	2.8	3.2	20	20.8	3.1	3.6
VS			2.3		2.3	2.1	2.2	17.8	18.1	2.5	2.5
Chemical composition	C		36.3		36.5	33.9	36.1	41.2	43.9	38.5	40.1
	H		4.6		4.7	4.9	4.5	6.5	6.1	5.6	5.2
	O		29.1		27.1	28.5	28.1	29.1	32.2	26.8	28.8
	N		2.8		2.7	3	3.1	4.8	5.3	5.4	6.5
	S		0.3		0.3	0.5	0.6	0	0	0.1	0.1
	Cl		0		0.1	0.1	0	0.1	0.2	0	0.1
Caloric value (Colorimeter)			3275.00	3410.00	3213.00	3275.00	4310.90	4431.80	3884.80	3712.80	
Heavy metals	As	mg/kg	N.D	N.D	N.D	N.D	N.D	N.D	0.1	N.D	
	Cd		N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	
	Cr		3.9	4.7	4.5	N.D	N.D	N.D	3.5	15.4	
	Cu		22.4	33.9	19.1	17.5	0.4	0.1	3.1	2.1	
	Pb		N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	
	Ni		1.2	1.8	0.4	0.8	0.3	0.6	0.4	0.1	
	Zn		129	115	139	134	15	16.1	24.1	11.7	
	Hg		N.D	N.D	N.D	N.D	N.D	N.D	N.D	0.1	

Table 7. Organic waste (pig manure, food waste, excretion, and thickened sewage sludge) sample analysis data (water quality analysis).

Items	Units	Farm 1	Farm 2	Farm 3	Farm 4	Food Waste 1	Food Waste 2	Excretion	Thickened Sewage Sludge
BOD	mg/L	27,541.8	27,631.5	29,841.5	30,806.4	160,074.8	155,245.3	9845.5	17,218.0
COD_{Mn}		22,318.1	22,763.5	21,874.1	23,645.3	109,031.6	127,659.1	8078.5	13,789.0
CODcr		60,978.5	51,024.1	54,264.3	57,350.1	215,177.9	244,555.4	34,996.1	71,909.5
SS		29,832.1	29,058.4	27,373.5	28,167.5	169,153.1	175,323.2	15,616.0	26,323.5
Nor		148.1	167.3	194.5	124.7	613.5	794.6	93.4	139.8
T-N		4402.0	5400.9	4156.8	3982.8	6151.3	6389.1	1383.3	2427.5
T-P		880.1	817.7	842.3	847.5	770.6	801.0	221.1	794.8
Total coliforms	total coliforms/mL	173,000	167,000	159,000	197,000	6200	4300	25,300	37,100
NH_3-N	mg/L	1937.0	1810.0	2188.0	1753.0	379.1	435.8	987.1	174.1
NO_2-N		210.1	276.6	344.5	244.5	19.8	24.6	161.5	N.D
PO_4-P		47.5	37.1	14.8	26.8	54.7	39.5	7.4	134.7
Alkalinity		15,251.0	20,890.0	16,758.0	18,934.0	2100.0	1567.0	3051.0	643.0

3.2. Solid Content of Organic Waste

The solid content of the organic wastes (TS and VS) is shown in Figure 7. The planned pig manure content was 4.5% of the TS and 3.0% of the VS. However, the actual average inflow was 4.9% of the TS and 3.4% of the VS, slightly higher than the planned amount. The planned food waste content was 21.0% of the TS and 17.8% of the VS, whereas the actual inflow average was 15.7% of the TS and 13.9% of the VS. The planned excretion input was 3.15% of the TS and 2.31% of the VS. These were higher than the actual average inflow of 2.0% and 1.4%, respectively, because of rainwater inflow into the septic tank. The planned thickened sewage sludge input was 3.68% of the TS and 2.84% of the VS, and the actual inflow average was 3.1% of the TS and 2.6% of the VS. Lastly, the planned mixed organic content after pretreatment was 5.94% of the TS and 4.7% of the VS, and the actual inflow average was 70% lower at 4.1% of the TS and 3.3% of the VS. Although the amount of solid content of the organic waste was lower than planned, the total amount of solids content was not artificially adjusted for experimental reasons as this was a large-scale actual treatment facility rather than an experimental setup. The full-scale anaerobic digester was designed to handle high organic loads (3–4 kg VS/m^3/day), so low organic loads below 1 kg VS/m^3/day were not a problem. The average organic matter removal efficiency (volatile solids basis) was 64%.



(a)

Figure 7. Change in the TS and VS content of (**a**) pig manure, (**b**) food waste, (**c**) excretion, (**d**) thickened sewage sludge, and (**e**) mixed waste.

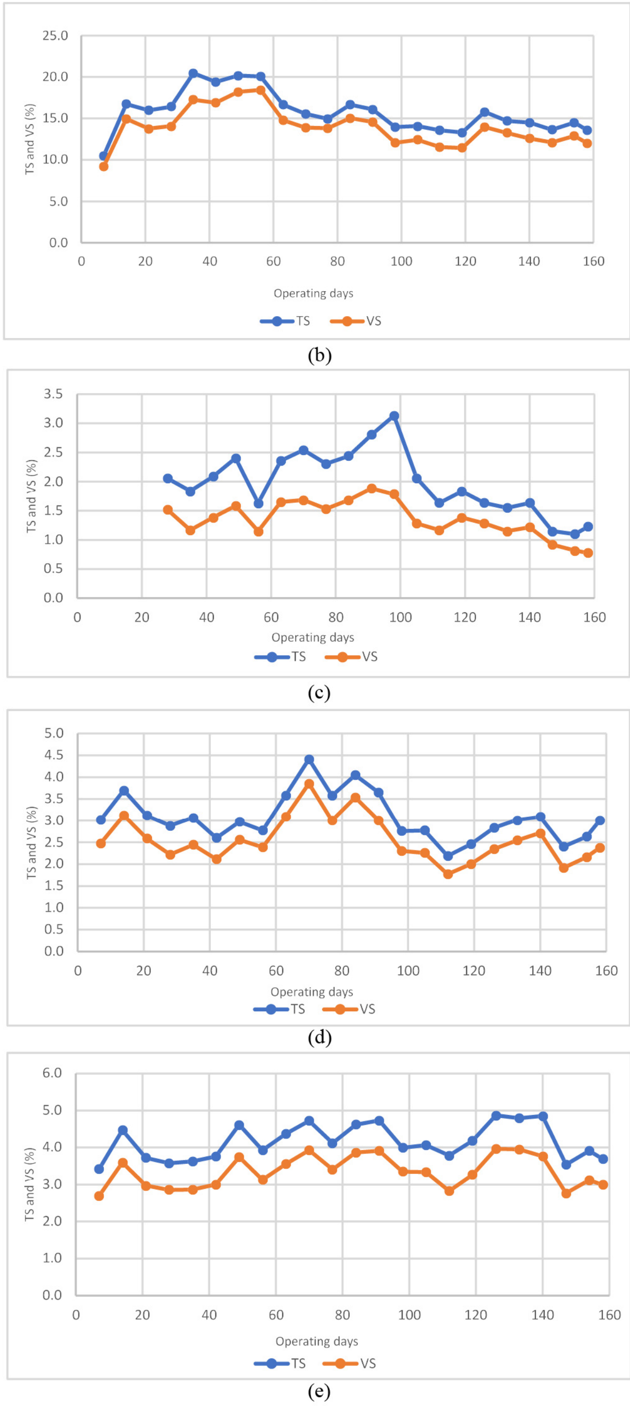


Figure 7. Change in the TS and VS content of (**a**) pig manure, (**b**) food waste, (**c**) excretion, (**d**) thickened sewage sludge, and (**e**) mixed waste.

3.3. Full-Scale Horizontal Anaerobic Co-Digestion Facility Operation

3.3.1. Full-Scale Horizontal Anaerobic Digester

The anaerobic digester comprised four reactors, A, B, C, and D. The size of each reactor was 10.7 mW × 27.3 mL × 11.9 mH (9.5 mHe), and the effective volume was 2775 m^3. Vertical impellers were installed along the horizontal axis and agitated at 1 RPM. This study was not of a laboratory or pilot-study scale, at which one can artificially adjust organic waste input for experimental purposes, but one that had to be able to secure the operational capability to treat local organic waste for 365 days stably. The anaerobic digester was operated for 158 days. The first three months were the stabilization period, in which organic waste was gradually increased after inoculation, and then the planned flow rate was processed stably for the last two months. Throughout the entire operating period, the operational status of the anaerobic digester was expressed as the average value of the four reactors.

3.3.2. Results of the Full-Scale Horizontal Anaerobic Digester Operation

Factors that indicate the operating state of anaerobic digesters include HRT, pH, alkalinity, VFAs, TS, VS, T-N, NH_4-N, gas production rate, and gas composition. The planned HRT was 35 days. During operation, the actual HRT was 42–68 days for the initial 98 days and 35 for the last 60 days, confirming that the planned HRT was maintained. Figure 8 presents changes in pH and temperature. pH and water temperature, the most important factors in the operation of the anaerobic digester, maintained stable values without significant changes throughout the period, except for during the early seeding stage. The average pH was maintained at 7.7 (highest, 7.9; lowest, 7.1), and the organic acid concentration was maintained at a low level of 356–802 mg/L after 30 days of operation. Water temperature was stable at 35–40 °C, a range of mesophilic digesters, from 80 days after initiating the operation.

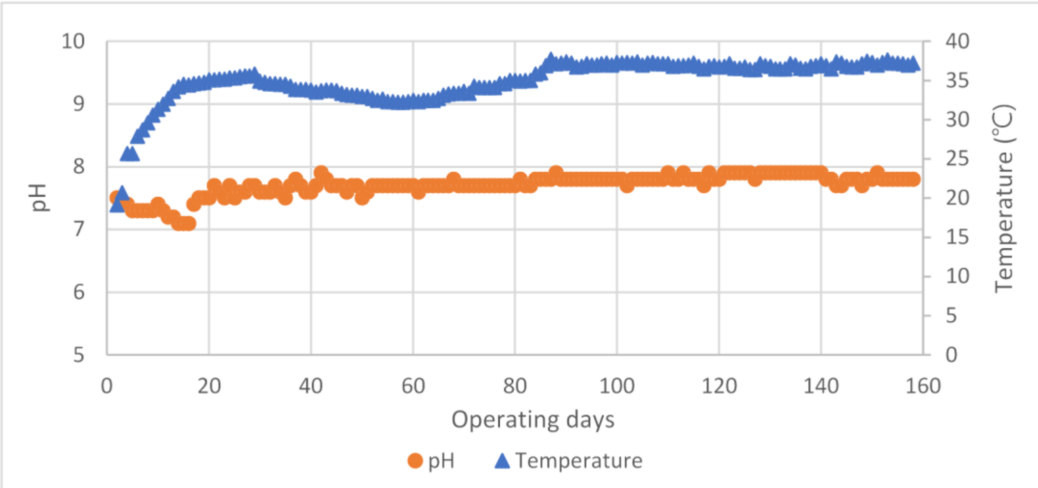


Figure 8. Change in pH and temperature during operation days.

Figure 9 presents the changes in alkalinity, which was continuously maintained at >5000 mg/L after 20 days and at 8000–9000 mg/L after 40 days. The VFA/alkalinity ratio remained somewhat low at 0.04–0.06. The main factors of the anaerobic digestion tank were maintained throughout the operation, confirming that the mixed waste of pig manure, food waste, excretion, and thickened sewage sludge was treated with rigor. The organic loading rate of the digester gradually increased and maintained a monthly average range of 0.96–0.99 kg VS/m^3/day after 65 days of operation and remained low at <1 kg VS/m^3/day throughout the operation. Therefore, the organic matter removal rate was maintained at a low level, with an average of 64%. As the inefficiency of digester operation increases when the organic matter content of the inflow waste is low, managing organic waste intake is crucial to operating and maintaining the digester efficiently.

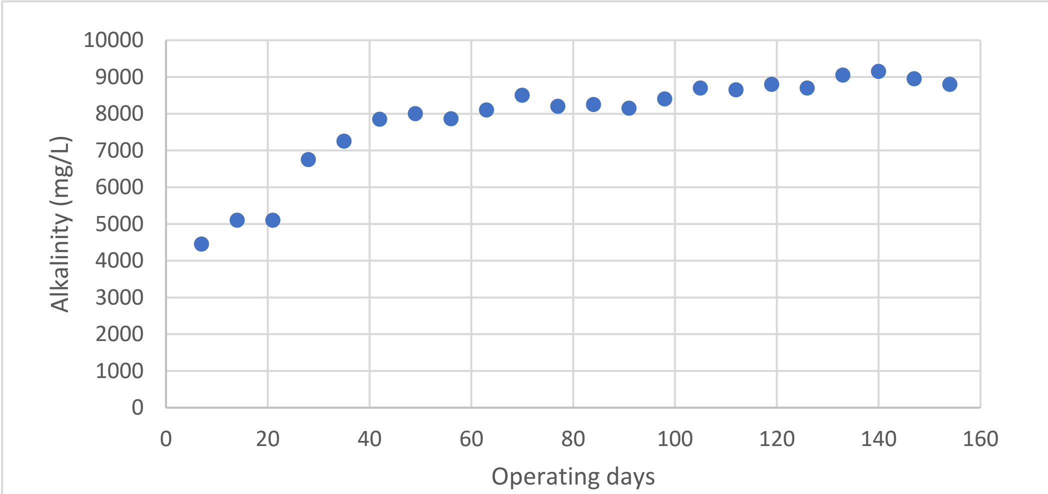


Figure 9. Change in alkalinity across operating days.

Figure 10 illustrates the changes in TS and VS, allowing us to determine the organic waste. Influent TS and VS were on average 4.2% and 3.4%, respectively. However, they deviated significantly throughout the operating period (TS, 2.8–7.2%; VS, 2.0–6.2%). From February to July 2020, a total of 158 days, four types of organic waste were introduced. Pig manure, food waste, and excretion were brought in on weekdays using a tanker truck. Thickened sewage sludge was introduced daily. Maintaining consistent inflow characteristics proved to be challenging during the operation of the full-scale facility. Despite significant variations in influent TS and VS, their average effluent concentrations were found to be 2.2% (ranging from 2.0% to 3.3%) and 1.5% (ranging from 1.2% to 1.5%), respectively, over a normal operating period of 60 days. The average organic matter removal efficiency (volatile solids basis) was 64%.

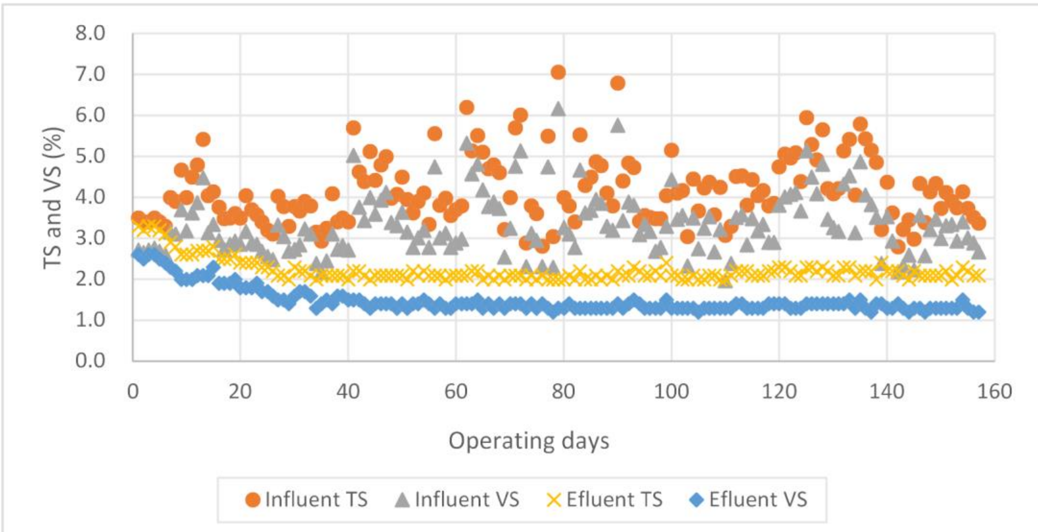


Figure 10. Changes in influent and effluent TS and VS.

The digestion gas was measured at the rear end of the gas storage tank, and the volume of digestion gas generated is shown in Figure 11. After the initial stabilization period, biogas was produced stably after 80 days, and the organic matter content of the input waste suddenly decreased at approximately 140 days, when the biogas production was reduced. After the organic matter content returned to normal, biogas production was restored. Initially, in the design stage of the anaerobic digester, 8825 Nm^3/day of biogas and 5294 Nm^3/day of methane gas were expected. Meanwhile, an average 5571 Nm^3/day biogas and 3677 Nm^3/day methane gas were produced across the entire operating period. The average for a normal operating period of 60 days was 7221 Nm^3/day of biogas (81.8% compared to design) and 4971 Nm^3/day of methane gas (designed compared to 93.8%), recording low performance due to the low organic matter content of the input waste. However, the average methane content was 64.8% during the operation period and 68.8% during the normal 60-day operation period, making it easy to produce electricity and heat energy using gas at the downstream facility.

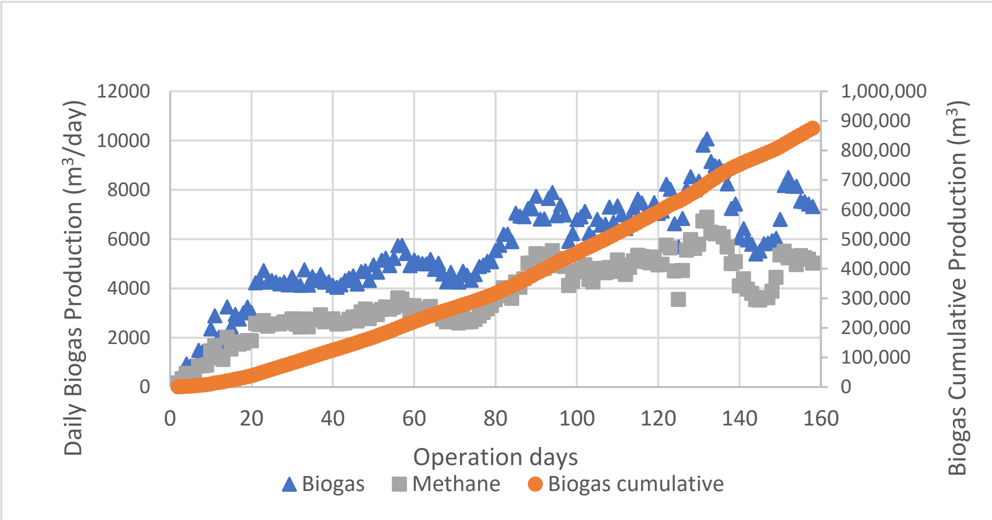


Figure 11. Biogas production.

Table 8 presents the rate of generation of methane gas for each brought-in waste. When the operation data were compared with the BMP test conducted during the design of the anaerobic digester, the methane production rate in all organic waste exceeded the BMP test results, indicating stable operation. The difference in methane production rate between the BMP test and the facility could be due to experimental errors. However, since the methane production rate in the facility exceeded that of the BMP test in all aspects, the increased methane production can be attributed to the synergistic effect of co-digestion [33].

Table 8. Methane production rate.

Gas Production Rate	Unit	Substrate				
		Pig Manure	Food Waste	Excretion	Thickened Sewage Sludge	Mixed
BMP Test	Nm^3CH_4/kg VSin	0.30	0.47	0.22	0.23	0.37
Operation Data		0.35	0.60	0.26	0.28	0.39

3.3.3. Effect of Parameters on Biogas Production and Methane Content

The results of the multiple regression analysis examining the effects of temperature, pH, and influent vs. on biogas production and methane content are shown in Table 9. Temperature, pH, and influent VS were set as independent variables, and biogas production and methane content were set as dependent variables. The higher the temperature, pH, and influent VS, the higher the biogas production and methane content, while the influent vs. did not have a significant effect on the methane content.

Table 9. The effects of temperature, pH, and influent VS on biogas production and methane content.

Dependent Variable	Independent Variable	Unstandardized Coefficient		Standardized Coefficient	t	p	VIF
		B		SE		ß	
Biogas Production	Temperature	295.652	30.835	0.427	9.588 ***	0.000	1.599
	pH	6122.640	498.053	0.552	12.293 ***	0.000	1.621
	Influent VS	217.331	100.381	0.078	2.165 *	0.032	1.046
	Durbin-Watson = 1.825, R^2 = 0.810, Adj-R^2 = 0.806, F = 217.220 *** ($p < 0.001$)						
Methane Content	Temperature	0.787	0.114	0.477	6.916 ***	0.000	1.599
	pH	8.276	1.838	0.313	4.503 ***	0.000	1.621
	Influent VS	0.629	0.370	0.095	1.697	0.092	1.046
	Durbin-Watson = 2.070, R^2 = 0.544, Adj-R^2 = 0.535, F = 60.898 *** ($p < 0.001$)						

* $p < 0.05$, *** $p < 0.001$.

4. Conclusions

This study presented the results after 158 operation days of Korea's first large-scale anaerobic co-digestion facility for four types of organic waste (food waste, pig manure, excretion, and thickened sewage sludge) at 320 m^3/day using an anaerobic digestion tank equipped with a vertical agitator using the rotation of the large horizontal axis.

In order to minimize potential issues that may occur when scaling up anaerobic digestion, several measures were taken, including the installation of adequate pretreatment facilities, securement a sufficient retention time of 35 days, and improvement of the mixing efficiency by installing a horizontal anaerobic digester with a large agitator. Despite the irregular inflow of organic waste, all parameters of the anaerobic digester were maintained, and a stable treatment efficiency was observed during operation. During the last 60 days of normal operation, the HRT was 35 days, and the organic matter load rate was maintained below the average of 1 kg VS/m^3/day. The methane production rate was 0.35 Nm^3CH_4/kg VS, 0.6 Nm^3CH_4/kg VS, 0.26 Nm^3CH_4/kg VS, and 0.28 Nm^3CH_4/kg VS for pig manure, food waste, excretion, and thickened sewage sludge, respectively. The average methane content of the biogas was 68.8%. These results confirm that various organic wastes can be merged and treated stably using an anaerobic digestion tank equipped with a vertical agitator by horizontal axis rotation. It is necessary to study whether it can be handled stably despite a high organic loading rate (3–4 kg VS/m^3/day) in this facility. This study presents the first successful case of a large-scale anaerobic co-digestion facility in Republic of Korea that generates biogas from four types of organic waste (pig manure, food waste, excretion, and thickened sewage sludge). As such, the findings of this study can provide a valuable basis for the design, construction, and operation of anaerobic co-digestion facilities.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Modeling Purpose

Verification of the specifications and placement of the applied agitator through computational fluid dynamics.

Appendix B. Type of Modeling, Boundary Conditions, and Others

- Program: Fluent v6.3.26
- Numerical methods: Finite-volume method
- Grid: Unstructured mesh

Table A1. Application model parameters and boundary conditions.

Item		Content
Model	Turbulent Model	K-ε turbulence model Steady State Analysis
	Multiphase	Phase: 2 (Water, Sludge) It is assumed that 6.3% TS sludge is always flowing in, and there is no chemical reaction between phases
Material Property	Sludge	Density: 1.1 kg/m^3 Viscosity: 0.00152 kg/m·s Under TS, 6.3%; VS, 4.9%, the specific gravity is 1.008 kg/m^3, Temperature: 38 °C
Basic condition	Operating Condition	Gravity: 9.81 m/s^2 Standard atmospheric pressure
Boundary Conditions	Inlet (sludge)	Velocity—Inlet: 0.05 m/s (80 m^3/day, 150 A pipe inflow rate) Second Phase VF: 0.063 (TS 6.3%) Temperature: 38 °C
	Inlet (circulation)	Velocity—Inlet: 0.087 m/s Second Phase VF: 0.029 (TS 2.9%)
	Rotation Area	Motion Type: Moving Reference Frame Angular-Velocity: 1.0 RPM
	Wall	Exterior wall and floor of the digester Impeller: No Shear Condition Digester upper water surface layer: Free Slip Condition
	Outlet	Naturally discharged under atmospheric pressure

Appendix C. Analysis of Results

- The results indicated that the flow velocity distribution changed according to the position of the agitator impeller.
- The swirling flow was reduced because of the bulkhead, and the flow effect occurred in the corner.
- There was a low speed ($\leq$0.1 m/s) area in the rotating shaft. However, the flow speed of the upper and lower parts was 0.2 m/s, which appeared to give a sufficient stirring effect.
- The strength of the swirling flow increased as it exited the agitator.
- The largest displacement vector was observed at the impeller location.

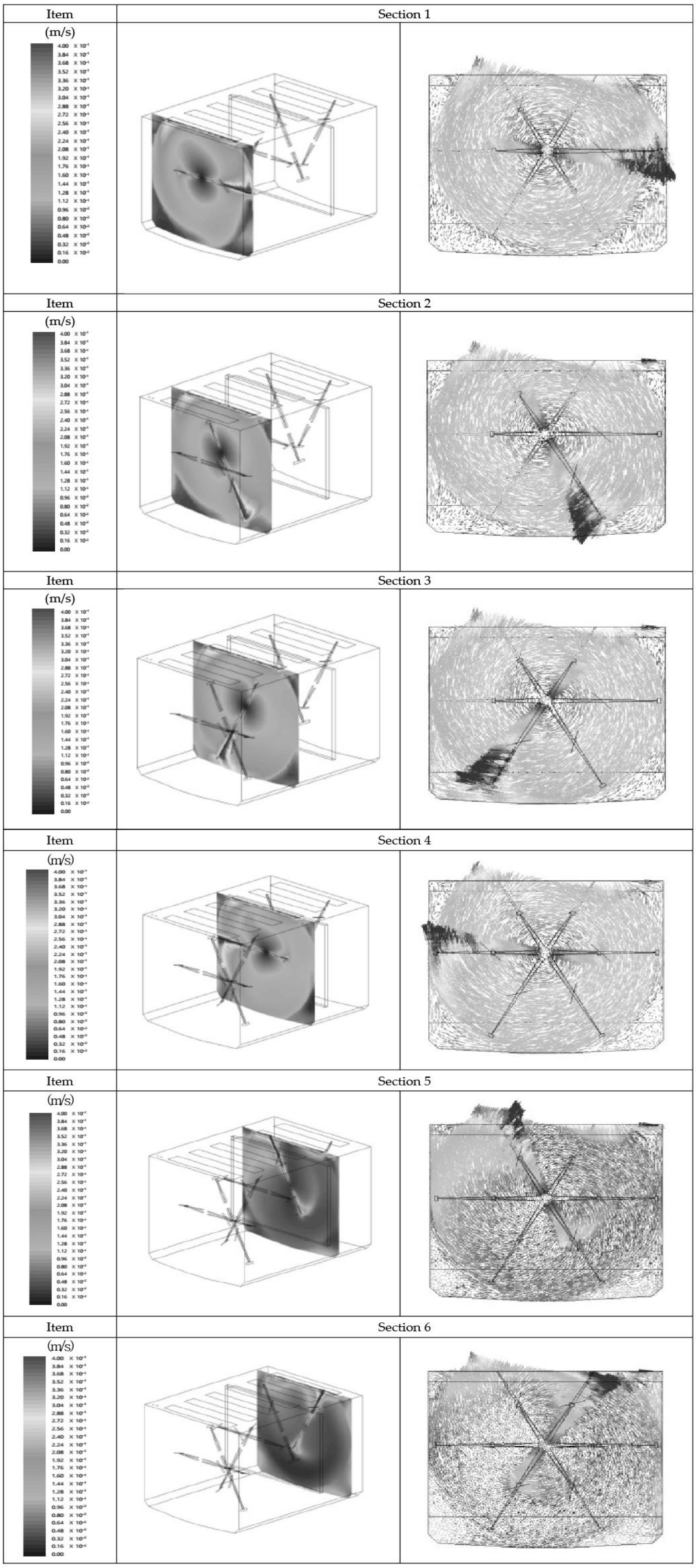

Figure A1. Flow velocity distribution as per the CFD simulation.

Appendix D. Analysis of Results (Concentration Distribution)

- A low-concentration area was observed in the center owing to the up- and downstream flow based on the bulkhead. However, the rotation of the agitator removed the low-concentration area through repetitive maxing.
- A relatively uniform concentration distribution with a concentration difference of <5% according to the position of the impeller was confirmed.

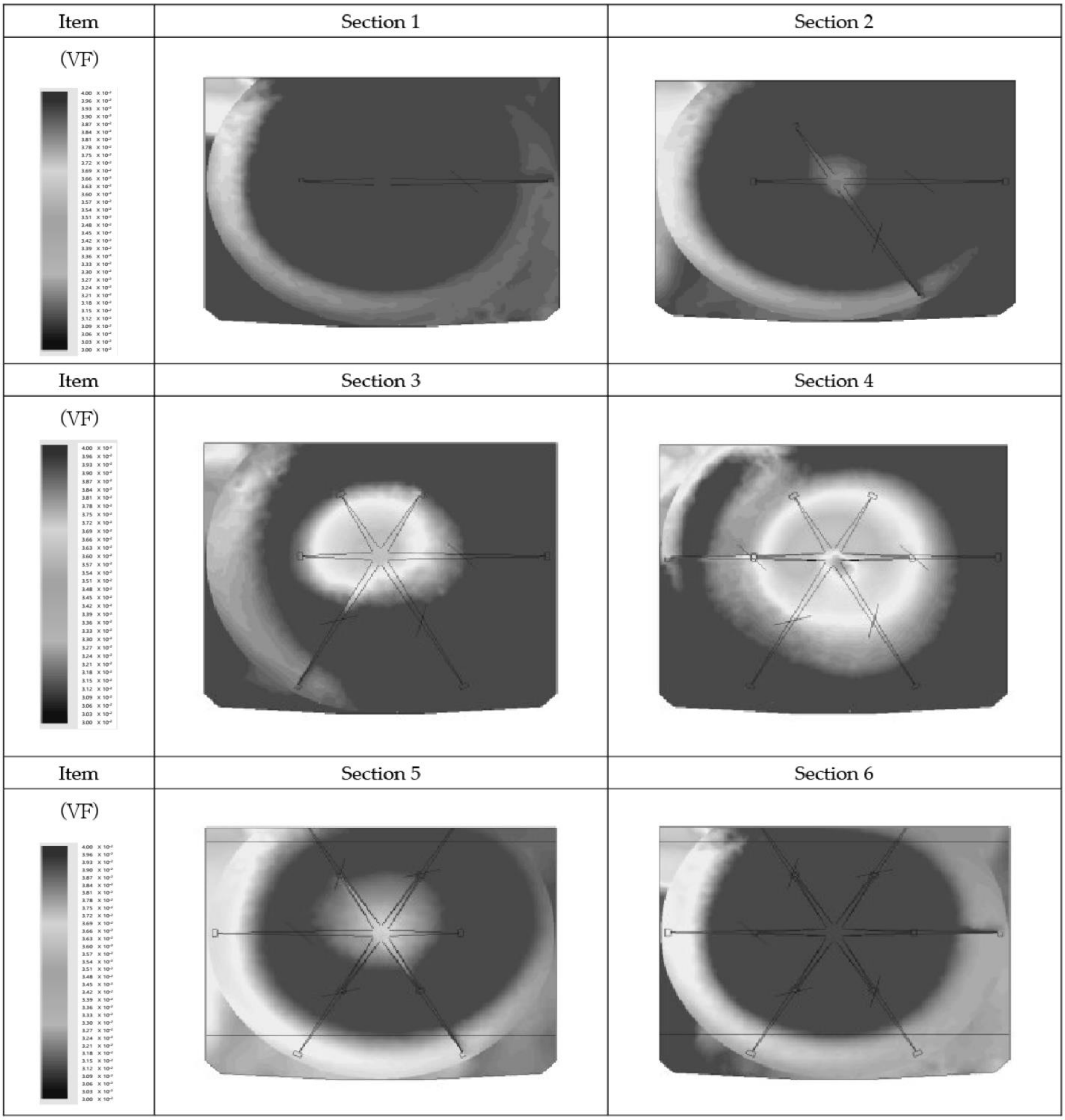

Figure A2. Concentration distribution as per the CFD simulation.

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